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Wind energy generation systems -
Part 5: Wind turbine blades

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IEC Secretariat
3, rue de Varembé
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
info@iec.ch
www.iec.ch

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Wind energy generation systems - Part 5: Wind turbine blades

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IEC 61400-5 edition 1.1 contains the first edition (2020-06) [documents 88/759/FDIS and 88/767/RVD] and its amendment 1 (2025-08) [documents 88/1086/FDIS and 88/1107/RVD].

In this Redline version, a vertical line in the margin shows where the technical content is modified by amendment 1. Additions are in green text, deletions are in strikethrough red text. A separate Final version with all changes accepted is available in this publication.

International Standard IEC 61400-5 has been prepared by IEC technical committee 88: Wind energy generation systems.

The text of this International Standard is based on the following documents:

FDIS	Report on voting
88/759/FDIS	88/767/RVD

Full information on the voting for the approval of this International Standard can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

Future standards in this series will carry the new general title as cited above. Titles of existing standards in this series will be updated at the time of the next edition.

A list of all parts of the IEC 61400 series, under the general title *Wind energy generation systems*, can be found on the IEC website.

The committee has decided that the contents of this document and its amendment will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn, or
- revised.

INTRODUCTION

The blades of a wind turbine rotor are generally regarded as one of the most critical components of the wind turbine system. In this International Standard, a minimum set of requirements for the design and manufacturing of wind turbine blades are defined.

An approach to a structural design process for the blade is set forth in the general areas of blade characteristics, aerodynamic design, material requirements and structural design. Furthermore, in order to efficiently facilitate the transfer of a blade design to the production environment, this document includes demands for designing for manufacturing.

The requirements for structural design of the wind turbine blade have been developed in a manner to reward innovation, validation, quality and testing. Specifically, the designer will be able claim lower partial safety factors based on, among other items, the diligence of the validation of models and the correlation to testing results.

To ensure a production environment that can facilitate the manufacturing of a blade in accordance with the design, the manufacturing requirements included in this document provide a minimum basis for a quality management system and workshop requirements. In addition, requirements for blade handling, operation and maintenance are described in the close of this document.

WIND ENERGY GENERATION SYSTEMS –

Part 5: Wind turbine blades

1 Scope

This part of IEC 61400 specifies requirements to ensure the engineering integrity of wind turbine blades as well as an appropriate level of operational safety throughout the design lifetime. It includes requirements for:

- aerodynamic and structural design,
- material selection, evaluation and testing,
- manufacture (including associated quality management),
- transportation, installation, operation and maintenance of the blades.

The purpose of this document is to provide a technical reference for designers, manufacturers, purchasers, operators, third party organizations and material suppliers~~, as well as to define requirements for certification~~.

With respect to certification, this document provides the detailed basis for fulfilling the current requirements of the IECRE system, as well as other IEC standards relevant to wind turbine blades. When used for certification, the applicability of each portion of this document should be determined based on the extent of certification, and associated certification modules per the IECRE system.

The rotor blade is defined as all components integrated in the blade design, excluding removable bolts in the blade root connection and support structures for installation.

This document is intended to be applied to rotor blades for all wind turbines. For rotor blades used on small wind turbines according to IEC 61400-2, the requirements in that document are applicable.

At the time this document was written, most blades were produced for horizontal axis wind turbines. The blades were mostly made of fiber reinforced plastics. However, most principles given in this document would be applicable to any rotor blade configuration, size and material.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60050-415, *International Electrotechnical Vocabulary (IEV) – Part 415: Wind turbine generator systems*

IEC 61400-1, *Wind energy generation systems – Part 1: Design requirements*

IEC 61400-2, *Wind turbines – Part 2: Small wind turbines*

IEC 61400-3-1*, Wind energy generation systems – Part 3-1: Design requirements for fixed offshore wind turbines*

IEC 61400-3-2, *Wind energy generation systems – Part 3-2: Design requirements for floating offshore wind turbines*

IEC 61400-23, *Wind turbines – Part 23: Full-scale structural testing of rotor blades*

IEC 61400-24, *Wind energy generation systems – Part 24: Lightning protection*

~~ISO/IEC 17021-1, *Conformity assessment – Requirements for bodies providing audit and certification of management systems – Part 1: Requirements*~~

ISO 10474, *Steel and steel products – Inspection documents*

ISO 2394, *General principles on reliability for structures*

ISO 9000, *Quality management systems – Fundamentals and vocabulary*

ISO 9001, *Quality management systems – Requirements*

EN 10204, *Metallic products – Types of inspection documents*

ISO 16269-6, *Statistical interpretation of data – Part 6: Determination of statistical tolerance intervals*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60050-415 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
blade root
that part of the rotor blade that is connected to the hub/pitch-bearing of the rotor

3.2
blade subsystem
integrated set of items that accomplish a defined objective or function within the blade (e.g., lightning protection subsystem, aerodynamic braking subsystem, monitoring subsystem, aerodynamic control subsystem, etc.)

3.3
buckling
instability characterized by a non-linear increase in out of plane deflection with a change in local compressive load

3.4
characteristic value
value having a prescribed probability of not being attained (i.e. an exceedance probability of less than or equal to a prescribed amount)

Note 1 to entry: See 61400-1.

3.5
chord
length of a reference straight line that joins the leading and trailing edges of a blade aerofoil cross-section at a given spanwise location

3.6
creep
time-dependant increase in strain under a sustained load

3.7
design limits
maximum or minimum values used in a design

3.8
design loads
loads the blade is designed to withstand, including appropriate partial safety factors

3.9
design properties
material and geometric properties (including design limits)

3.10
edgewise
direction that is parallel to the local chord

3.11
environmental conditions
characteristics of the environment (wind, altitude, temperature, humidity, etc.) which may affect the wind turbine blade behaviour

3.12
flapwise
direction that is perpendicular to the surface swept by the undeformed rotor blade axis

3.13
flatwise
direction that is perpendicular to the local chord, and spanwise blade axis

3.14
inboard
towards the blade root

3.15
lead-lag
direction that is parallel to the plane of the swept surface and perpendicular to the longitudinal axis of the undeformed rotor blade

3.16
limit state
state of a structure and the loads acting upon it, beyond which the structure no longer satisfies the design requirement

3.17
load envelope
collection of maximum design loads in all directions and spanwise positions

3.18
natural frequency
eigen frequency
frequency at which a structure will vibrate when perturbed and allowed to vibrate freely

3.19
partial safety factors
factors that are applied to loads and material strengths to account for uncertainties in the representative (characteristic) values

3.20
prebend
blade curvature in the flapwise plane in the unloaded condition

3.21
spanwise
direction parallel to the longitudinal axis of a rotor blade

3.22
stiffness
ratio of change of force to the corresponding change in displacement of an elastic body

3.23
strain
ratio of the elongation (or shear displacement) of a material subjected to stress to the original length of the material

3.24
sweep
blade curvature in the lead-lag plane in the unloaded condition

3.25
twist
spanwise variation in angle of the chord lines of blade cross-sections

3.26
critical to quality
CTQ
process or design value that is measurable and specifies critical acceptance criteria

4 Notation

4.1 Symbols

F	load
F_d	design value for the load
F_k	characteristic value for the load
R	resistance of material or structure against the corresponding limit state
R_k	characteristic material resistance
PSF	Partial Safety Factor
S()	function for structural response to the load
T_g	glass transition temperature
$p_{\perp\parallel}$ (−)	negative Puck inclination parameter
$p_{\perp\parallel}$ (+)	positive Puck inclination parameter

4.2 Greek symbols

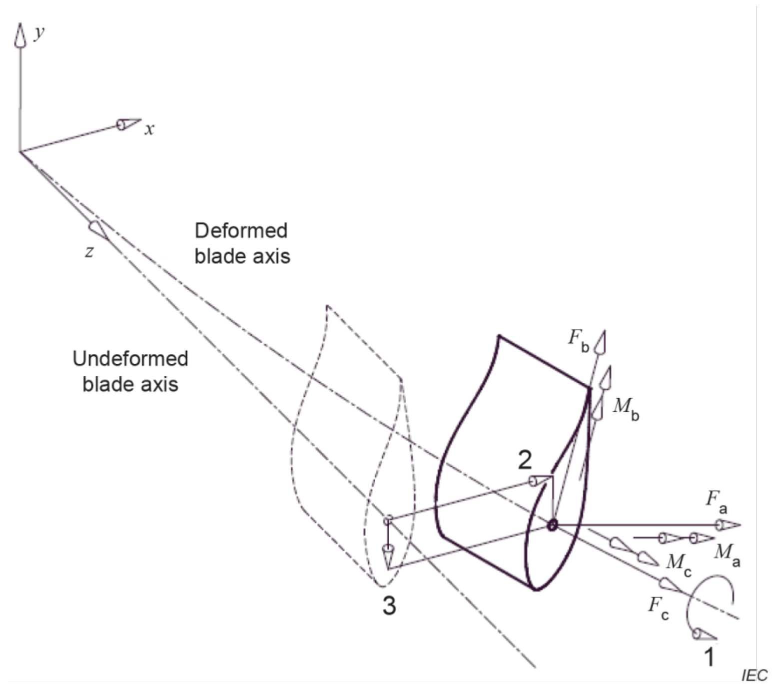
γ	Partial safety factor

4.3 Subscripts

m	materials
m0	materials as a “base” material factor (to be included in all analyses)
m1	materials for environmental degradation (non-reversible effects)
m2	materials for temperature effects (reversible effects)
m3	materials for manufacturing effects
m4	materials for calculation accuracy and validation of method
m5	materials for load characterization
n	consequence of failure
f	factor for loads

4.4 Coordinate systems

Coordinate systems for loads and design reference are shown in Figure 1 and Figure 2.

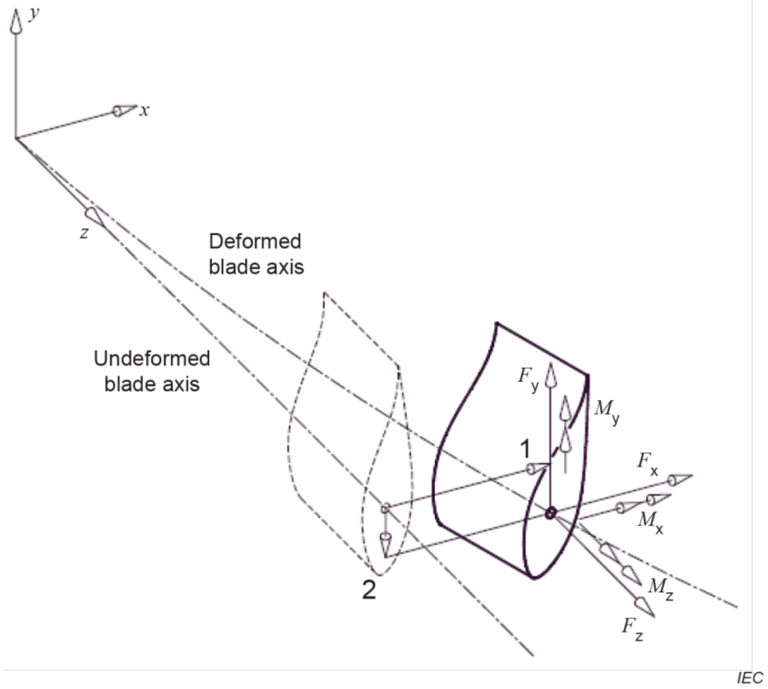


Loads are along and perpendicular to the local blade chord directions.

Key

M_a	edgewise bending moment
M_b	flatwise bending moment
M_c	torsion moment
F_a	flatwise shear force
F_b	edgewise shear force
F_c	axial force
1	torsion angle
2	flapwise translation
3	lead-lag translation

Figure 1 – Chordwise (flatwise, edgewise) coordinate system



Loads are along the rotor plane reference directions.

Key

M_x	lead-lag bending moment
M_y	flapwise bending moment
M_z	torsion moment
F_x	flapwise shear force
F_y	lead-lag shear force
F_z	spanwise force
1	flapwise translation
2	lead-lag translation

Figure 2 – Rotor (flapwise, lead-lag) coordinate system

5 Design environmental conditions

Wind turbine blades are subjected to environmental conditions that may affect their loading, durability and operation. To ensure the appropriate level of safety and reliability, the design environmental conditions shall be taken into account and explicitly stated in the design documentation. This shall include but is not limited to the environmental conditions specified in IEC 61400-1, IEC 61400-3-1 or IEC 61400-3-2, and IEC 61400-24 (for lightning).

The environmental conditions are divided into normal and extreme categories. The normal environmental conditions generally concern recurrent structural loading conditions, while the extreme environmental conditions represent infrequent external design conditions. The design load cases defined in IEC 61400-1, IEC 61400-3-1 or IEC 61400-3-2 include combinations of these environmental conditions with wind turbine operational modes and other design situations.

When additional environmental conditions not listed in the above references are specified by the designer, the parameters and their values shall be stated in the design documentation.

It shall be taken into account that these environmental conditions may vary for different phases of the product lifecycle (manufacturing, transport/storage, installation, operation or dismantling).

6 Design

6.1 Structural design process

6.1.1 General requirements

The structural design process shall ensure that the required operation safety levels are met for the entire design lifetime and loading of the blade.

The design shall be sufficiently described and specified to ensure that assumptions made during the design process can be met and complied with during the manufacturing process.

The allowable manufacturing tolerances and acceptance criteria shall be defined by the designer and specified in the design documentation.

Any of the requirements of this document may be altered if it can be suitably demonstrated that the safety of the wind turbine system is not compromised.

6.1.2 Building block approach for composite structural design

The traditional detailed design (analytic and numerical calculation together with validated material data and full blade testing) of FRP structures can be enhanced by a building-block approach, starting with coupon-level tests, analysis and testing of more complicated structures; and culminating in a full blade test. This relationship is shown in Figure 3, where increasingly more complex tests are developed to evaluate more complicated loading conditions and failure modes.

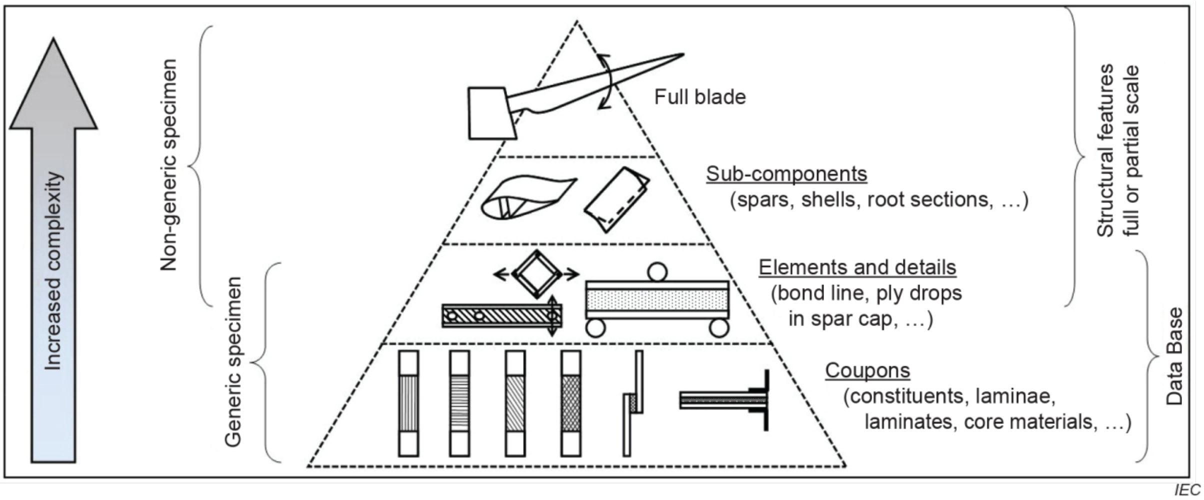


Figure 3 – The building block approach

The approach can be summarized as follows:

Coupons: A number of tests are conducted at the coupon level, where confidence in repeatable physical properties is developed. Procurement specifications are developed for the individual constituents, and allowable design variables developed for lamina/laminate combinations.

Elements and details: Critical areas from the design analysis identify elements for further testing and analysis at the design conditions with representative specimens. This may include such tests as the spar cap to web bond line or ply drops in the spar cap laminate.

Sub-components: Parts and sections representative of the blade design are tested to evaluate specific loading conditions and failure modes. Examples include spars, shells and root sections. The test components may be full or partial scale where demonstrated to be representative.

Full blade: A full blade or significant part of a blade, representative of the blade design is tested to evaluate specific loading conditions and failure modes. The blade may be full or partial scale where demonstrated to be representative.

The number of tests required for each level should be tailored for each design activity, with the blade designer responsible for the development of a reasonable number of tests at each stage.

Tests on the element and detail as well as sub-component level will increase the confidence in the structural design.

For design values (strength, stiffness, etc.) developed from test at any building block level (material sample, sub-component, etc.), the validity of such design values shall be described and limited by acceptance criteria[1] and tolerances to be met in the final design.

6.1.3 General blade design process

A typical process, provided for informative guidance only, for the design and analytical evaluation of a blade is illustrated in Figure 4. In addition to the steps shown, the design process can include the development of critical inputs, such as establishing aerodynamic characteristics of airfoils, and characterization of materials properties.

The iteration loops shown are only indicative and may not represent all specific design processes. For example, if an aerodynamic design evaluation is not found satisfactory, the designer may re-consider the airfoils used (as shown in the figure), or iterate at another step of the aerodynamic design process.

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[1] Note on acceptance criteria (example only): for a laminate coupon sample tested for fatigue strength, the acceptance criteria may amongst other include definition of raw materials (reference to material specifications), fiber volume fraction, fiber alignment angles, manufacturing and curing process, etc.

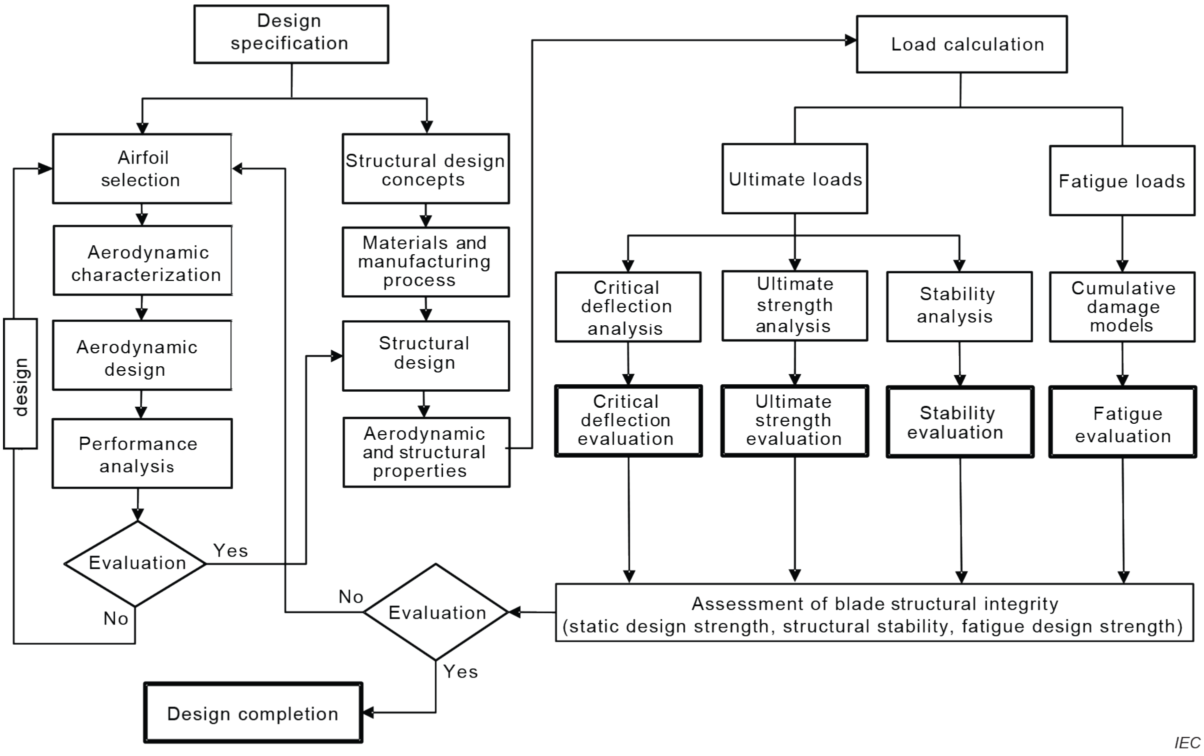

Figure 4 – Typical process for design and analytical evaluation of blade

As noted in Figure 4, the blade structural integrity is to be evaluated for avoidance of specific failure modes. Evaluations can be based on analysis or tests or a combination of analysis and tests (see building block approach, Subclause 6.1.2). This is in conformity with IEC standards (e.g., IEC 61400-1, IEC 61400-3-1, IEC 61400-3-2) which require the use of the limit states design approach.

In the most general sense, the limit states design approach involves the characterization of structural responses resulting from loads (e.g., stress, strain or deflection) and resistance to those responses (e.g., strength, stiffness). Partial safety factors (PSFs), γ, are applied to account for uncertainties in the calculated response and resistances so that the probability of exceeding limit states is acceptably low.

Characteristic loads are those predicted to occur with a specified probability. The design values for loads are determined by multiplying by loads partial safety factors, γ_f.

Resistance is normally a function of material properties. Characteristic resistance is calculated from test results, where the default is 95 % exceedance with 95 % confidence level according to ISO 16269-6. It should be stated if statistical tolerance limit factors for known or unknown population standard deviation are used.

The resistance of the structural materials as embodied in the full blade structure may be different than as measured at the coupon level. In some cases, this may be due to predictable effects of scale, geometry, and load-introduction. Other effects could include variations in material properties (e.g., composition, mechanical properties, orientation). The material partial safety factor, γ_m, is intended to cover combined uncertainties in the relationship between coupon-based resistance and the resistance in the as-built blade. Subclause 6.6.4 gives detailed definition of how γ_m is defined.

According to IEC 61400-1, partial safety factors for consequences of failure, γ_n, shall also be included. In principle, γ_n can be applied either as an increase in the response, or a decrease in resistance as shown in Figure 5.

In all verifications, the design value of response shall not exceed the design value of resistance. Figure 5 shows these two values being separated by a safety margin. Verification requires safety margin values greater than or equal to zero.

For some limit states, the relationship between material properties and resistance against failure in the limit state is not linear (e.g., in a fracture mechanics and buckling analyses). For such cases, the PSFs shall be applied in such way that they have a linear relation with the load carrying capability as in the following equation:

$$S(\gamma_\mathrm{f} \times F_\mathrm{k}) \le \frac{R_\mathrm{k}}{\gamma_\mathrm{m}\gamma_\mathrm{n}}$$

where S is a function for the structural response to the load and R_k is the characteristic material resistance.

This general formulation is shown in Figure 5, where partial safety factors are introduced in a relationship between the structural response due to loads and the resistance for the corresponding limit state.

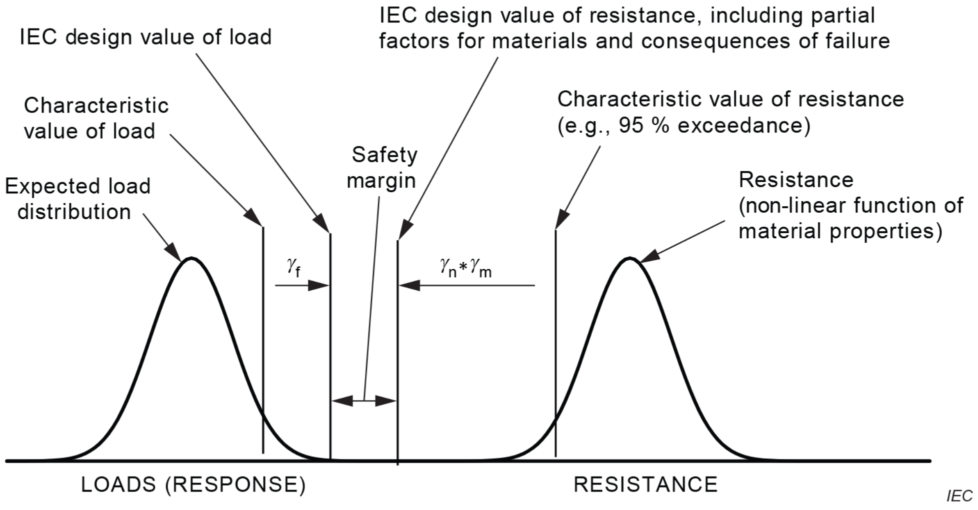

Figure 5 – Application of limit states design approach for blade verification

Material resistance may be expressed either in stress or strain.

As discussed in 6.6, γ_m is derived by consideration of numerous contributions to the overall resistance uncertainty. At the time this document was written, typical industry practice was consistent with the illustration in Figure 3, with material resistance developed by coupon-level testing to determine material properties which are then translated to blade-level using a value of γ_m that covers a wide number of uncertainties. Numerous strategies are possible by which uncertainties in the transfer of material-level properties to the resistance in the as-built blade can be reduced.

For example, by using the building block approach, a combination of failure modes and limit states are taken into account with a lower uncertainty with increased size and complexity of the building block tested. Obtained strength and stability values will define failure modes for material samples and sub-components, and shall be compared with analytical methods for validation.

6.1.4 Design loads

6.1.4.1 Design envelope

The design loads for a blade can be specified for a single wind turbine design, or it can be given as a wider load envelope intended to cover a range of wind turbine designs.

The defined loads/load envelope may be based on the design load cases specified in IEC 61400-1, including non-operational situations (e.g., transportation, handling, installation, maintenance, loading of attachment points). For offshore turbines, the requirements in IEC 61400-3-1 and IEC 61400-3-2 should be considered.

6.1.4.2 Load interaction

The structural characteristic of the blade interacts with its aerodynamic loading and the turbine controller. For a safe operation of the blade in rotational and stand still conditions, it shall be assured that any instability (e.g., flutter) or resonance as a result of the interaction of aerodynamic loading, blade structural design, turbine control (rotational speed, pitch angle, etc.) and support structure has been considered in the load calculation.

The structural design of the blade shall reflect the defined operational, transportation and handling load envelope, and the structural verification shall prove that the blade can withstand the specified ultimate and fatigue design loads.

6.1.4.3 Load envelopes

Due to the asymmetry of rotor blade structures, the assumed loads in the analysis may not reflect the most critical loading direction for any given failure mode. There are two approaches to account for the critical loading direction.

- Basic approach: Usage of four matched sets of loads (moments and forces) corresponding to the extremes of flatwise and edgewise loads. The angle of the resulting load vector shall be considered. For certain verifications, this may be insufficient to cover the most critical load directions for combined loading. This shall be considered in the design.
- Advanced approach: Consideration of all potentially critical loading directions within a cross section. Without further analysis of load criticality, a set of loads distributed evenly in at least twelve directions is considered sufficient for this approach.

The components of an extreme load envelope are not generally contemporaneous (happening at the same time) and therefore this loads envelope represents a conservative condition. This conservatism may be reduced by evaluating the structure for each of the contemporaneous loads that comprise the extreme load.

In general, it is sufficient to design for the resultant bending moments. However, this may not always be the most critical loading type for all failure modes. For example, the highest shear forces represent the most critical loads for the verification of bond strength. Torsional loading should also be considered.

To ensure that loads are calculated at a sufficient number of spanwise sections, loads shall be available at minimum 12 cross sections along the blade length (spanwise).

The spanwise distance between load definition sections shall not be larger than 2,0 × the smallest chord length for the given section, for the sections from root to 85 % of blade length.

Geometry or stiffness variations shall be considered during section selection.

6.2 Blade characteristics

6.2.1 Blade properties

Structural and aerodynamic properties of the blades are critical to the aero-elastic loading of the blade and turbine.

The characteristics of the blade shall be defined for use as input for loads calculation. These characteristics shall include mechanical and physical properties at discrete sections along the length of the blade, for the relevant degrees of freedom that are related to the relevant design states:

- distribution of aerodynamic profiles, chord, aerodynamic twist, and thickness;
- aerodynamic characteristics (i.e., lift, drag, and pitching moment coefficients as a function of angle of attack) associated with the aerodynamic profiles;
- elastic stiffness properties (e.g., flatwise and edgewise stiffness and if significant to the design, torsional and extensional stiffness) and their reference axes;
- distributions of mass and mass moments of inertia and the reference axis;
- elastic coupling (e.g., flatwise vs. edgewise, flatwise vs. torsion or similar, if significant to the design);
- structural damping.

Structural properties shall be defined for a minimum number of sections along the blade. These shall not be less than those specified for structural verification according to 6.6.3.1.

6.2.2 Functional design tolerances

Tolerances shall be defined for the following parameters:

- shape of the aerodynamic profiles, including but not limited to:
  - radius of the profile leading edge;
  - relative thickness of the profile;
  - local chord length;
- roughness of the profile surface;
- aerodynamic twist angle;
- blade length;
- geometric position of blade aerodynamic profiles relative to blade root reference;
- geometry and position of any static or moveable aerodynamic device (vortex generator, flaps, etc.);
- the nominal 0° pitch marking;
- blade mass;
- blade static moment (for each individual blade and relative to blades in a blade set);
- blade natural frequencies;
- angular and flatness tolerance for blade face flange.

Tolerance ranges for the above listed parameters shall be accounted for in the design evaluation of loads, performance and structural integrity, in case they are judged as not negligible for consideration of safe operation of the blade.

The actual values of the tolerances shall be specified and considered by the designer.

If the designer does not specify alternative values, the following values are generally acceptable without further technical justification.

• profile[2]	
– shape of the profile	±0,2 % × chord
– roughness of the profile surface[3]	$R_\mathrm{z} \leq 15$ µm
– local chord length (for the inboard 80% of span)	±1,0 % × chord
• twist angle distribution	±0,2°
• blade length	±0,1 % × length
• setup of 0° marking	±0,2°
• blade mass	±3,0 %
• blade static moment	±4,5 %
• blade static moment, difference in one set	±0,2 %
• blade natural frequency	±5,0 %

6.3 Aerodynamic design

6.3.1 General

The assessment of the aerodynamics of the rotor blade will generate input data for load calculations and power performance calculation evaluation based on both experimental and computational results.

6.3.2 Aerodynamic characteristics

The aerodynamics of the blade shall be characterized. The full 360° range of angle of attack and all flow regimes should be considered.

One or a combination of any of the following approaches shall be used to evaluate the aerodynamic characteristics of the blade (where appropriate, the models and tools employed shall be validated):

- 3D simulation (computational fluid dynamics, boundary element method, vortex lattice method, etc.);
- 2D simulation of the aerodynamic characteristics of the profiles;
- justified assumptions regarding the aerodynamic profiles characteristics for the range of angle of attack with flow separation;
- wind tunnel tests for at least the range of angle of attack to obtain the aerodynamic characteristics in the area of maximum positive and negative lift coefficient.

The evaluation shall take into account realistic Reynolds and Mach numbers.

To ensure a realistic load and performance analysis, the effect of blade roughness during operation should be considered. The evaluation defined above shall be done for a sufficient number of aerodynamic profiles to characterize the aerodynamic behavior of the whole blade.

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[2] The influence of these tolerances depends on the profile specific characteristics and the location on the blade surface; the blade leading edge and outboard areas are most sensitive to shape deviations and roughness.

[3] This tolerance applies to gelcoat and painted surfaces; soiled blade surfaces due to operation are not covered by this tolerance and shall be considered by suitable design assumptions.

As a minimum one aerodynamic profile with a relative thickness between 75 % and 50 %, one profile with a relative thickness between 50 % and 30 %, and two profiles with a relative thickness below 30 % shall be assessed.

3D effects shall be taken into account.

Any additional aerodynamic devices (flaps, vortex generators, serrations, etc.), which are planned to be used on the blade, shall be evaluated.

6.3.3 Power performance characterisation (informative)

The power performance of the blade should be considered to evaluate its efficiency. To get a reliable characterization of the rotor power characteristic the following points should be taken into account:

- reliable aerodynamic blade model, assessed according to 6.3.2;
- appropriate turbulence of the wind field;
- appropriate vertical gradient of the wind field;
- appropriate air density and temperature of the wind field;
- appropriate simulation model of the turbine control unit (speed and [single and/or collective] pitch control);
- influence of airfoil surface roughness that is representative of expected surface conditions.

The deformation of the blade (e.g., twist and profile deformations) during operation should be taken into account for a reliable power characterization.

6.3.4 Airfoil noise (informative)

The noise generation of the blade should be considered. Appropriate analytical or computational approach should be used and special aerodynamic devices present on the blade should be taken into account.

6.4 Material requirements

6.4.1 General

For fiber reinforced composite materials, the strength and stiffness values are dependent on the properties of the raw materials and the manufacturing processes.

The following steps are essential to ensure that the materials meet the design requirements:

- The design values for strength and stiffness of materials used for structural composite members shall be specified.
- Materials require a qualification proving that they meet the specified values. The qualification shall be documented and a process shall describe necessary tests to be performed.
- For raw materials for composite material manufacture, the designer should define critical parameters or values to be verified and/or tested during incoming goods inspections.

6.4.2 Material properties for blade design

6.4.2.1 Characterization

Material properties used for blade design includes design values for combined materials (e.g., fiber composites), bond lines (e.g., including strength of adhesive and complete bond line assembly), sandwich design (e.g., including sandwich core materials and their interaction with face sheets).

The material properties and design values are what determine material compliance against specific blade functional requirements and as such constitutes the basis for material selection. Material requirements for blade design are properties of the resulting material, product, or subsystem.

The designer shall select appropriate test specimens using manufacturing processes representative for those used in the blade serial production. It is recommended to follow the building block approach described in 6.1.2.~~ For certification purposes, the tests for establishing design values for structural verification shall be performed according to requirements specified in the relevant certification scheme, e.g.:~~

- ~~an accredited test organization;~~
- ~~a company approved by a suitable certification agency;~~
- ~~a non-certified company witnessed by the certification agency.~~

Due to the nature of composite materials, some material properties are best determined with element and/or component level specimen configurations.

The characterization of material mechanical properties shall be established based on statistical evaluation, such as mean values, standard deviation, etc. If not stated differently, a survival probability of 95 % with 95 % confidence level shall be used. Results on smaller scale tests may be used to estimate the scatter of larger scale tests.

In cases where test methods are not available, the materials mechanical properties may be documented by validated calculation methods, e.g., synthesized classical laminate theory (CLT), or failure models provided that the accuracy of the models can be demonstrated through validation by testing. Any uncertainty resulting from this shall be represented in the corresponding PSF.

The use of design values from recognized guidelines is acceptable. The source reference shall be stated, however it should be noted that the values used are often conservative.

Specimen conditioning/ageing:

For nominal design properties, specimens are tested without condition and ageing. If required in connection with specific material partial safety factors γ_{m1} as in 6.6.5.2, additional tests shall be carried out on specimens that have been conditioned/aged in accordance with the specific choice of partial safety factors.

Test temperature:

For nominal design properties, specimens shall be tested at room temperature. If required in connection with specific material partial safety factor γ_{m2} as 6.6.5.2, additional tests shall be carried out at the required temperatures in accordance with the specific choice of partial safety factors.

Manufacturing process:

For nominal design properties, specimens are tested without consideration of the effects of blade manufacturing tolerances.

Elastic properties:

For applications outside the extreme temperature range for the standard wind turbine classes according to the IEC 61400-1, the changes in elastic properties of blade materials shall be taken into account.

6.4.2.2 Fiber reinforced laminates

FRP (fiber reinforced plastic) materials consist of a fibrous reinforcing component material, which provides the main strength and stiffness properties, combined with a polymeric matrix component (resin) providing support, stress transfer and protection to the fibers.

Each individual laminate type (unidirectional, biaxial, and multiaxial) should be tested separately. The scope of required testing may be reduced (using a higher γ_{m3} and/or γ_{m4}, see 6.6.4) when the same constituents are used in the different laminates (e.g., UD, BX and Multiaxial laminates made from the same fibers, with similar lamina thicknesses, and with the same resin matrix), or when the test specimens are built with material combinations and lay-ups representative for the blade design.

The following material properties shall be tested, and statistically derived characteristic values for strength properties shall be obtained.

Physical properties for each test panel:

- fiber volume fraction and void content;
- state of cure (e.g., T_g for epoxy);
- cured ply thickness.

Static tests:

- longitudinal [0°] tensile: strength, modulus, strain, Poisson′s ratio;
- transverse [90°] tensile: strength, modulus, strain;
- longitudinal [0°] compression: strength, modulus, strain;
- transverse [90°] compression: strength, modulus, strain;
- in-plane shear: strength, modulus;
- interlaminar shear: strength (e.g., short beam).

Fatigue tests:

- longitudinal [0°]: strength

A reasonable spread of number of cycles shall be demonstrated e.g., 4 consecutive decades, with 3 samples in each decade. One of the decades shall exceed 10^6 cycles. If tests are done at only one R ratio, this should be $R = -1$. For compliance with the definition of "full fatigue characterization" in the selection of partial safety factors, the following test shall be performed: cyclic fatigue test with more than one representative R ratio (typically at $R = -1$, $R = 10$ and $R = 0{,}1$).

Alternatively, the following inverse slopes of the S-N-curve may be used in combination with appropriate partial safety factors (γ_{m4}) for fatigue strength verification without further validation (static strength and assumed Wohler slope in fiber direction), provided that the fiber volume content does not exceed 55 % (glass fiber) or 60 % (carbon fiber; only tows ≤ 50 K):

- glass/epoxy laminates = 10
- glass/polyester laminates = 9
- carbon/epoxy laminates = 14

6.4.2.3 Structural adhesive and bonded joints

Bonded joint strength (ultimate and fatigue) shall be evaluated using representative tests consistent with the partial safety factors according to 6.6.5.8 and 6.6.5.9. Fatigue shall be evaluated using a reasonable spread of the number of cycles (e.g., 4 consecutive decades, with 3 samples in each decade). One of the decades shall exceed 10^6 cycles. The bonded joint strength may be evaluated using more complex and realistic details with correspondingly lower safety factors.

It is possible to employ a fracture based approach. In this case, the fracture toughness shall be tested and statistically derived characteristic values determined.

The following properties shall be established for the adhesive material:

- static tensile and shear moduli;
- state of cure (e.g., minimum glass transition temperature, T_{g}, for epoxy).

The following properties of the adhesive material should be tested, and a minimum criterion should be established as requirement for blade design and material selection:

- creep;
- shrinkage.

Adhesives should not have any adverse effects on the materials to be joined.

6.4.2.4 Sandwich structures

For compliance with lower γ_{m3} and γ_{m4}, the following core material properties shall be tested, and their statistically derived characteristic values for strength properties shall be obtained:

- out-of-plane compression (strength, modulus);
- maximum processing temperature.

In order to get the lower γ_{m3} and γ_{m4}, the following sandwich properties shall be tested, and their statistically derived characteristic values for strength properties shall be obtained:

- out-of-plane shear (strength, modulus, strain);
- peel or face sheet adhesion strength;
- face sheet wrinkling.

The sandwich panel materials shall be representative of the core material, face sheets and interface characteristics used in design of the blade. If core materials with slits, holes or scrim are used they also shall be included.

6.4.2.5 Structural metallic materials

The following material properties shall be tested for each material (or guaranteed through recognized standards):

- tensile strength;
- yield strength;
- elongation to failure;
- impact absorbing energy.

6.4.2.6 Surface finishes

The following material properties shall be tested and a minimum criterion established as requirement for material selection.

- adhesion to substrate (e.g., pull off tests);
- flexibility or elongation at break;
- erosion resistance against rain and particle impingement, for materials used on leading edge and tip areas.

It shall be ensured that the materials are sufficiently resistant to environmental influences, such as humidity and UV radiation.

The impact resistance (hail) should be tested and a minimum criterion established as requirement for blade design and material selection.

6.4.2.7 Non-structural materials

All non-structural materials (such as sealant, fillers, balancing weights, lightning protection system components, or other equipment) shall be documented. It shall be ensured that their properties are suitable for the intended purpose, that they can withstand the strains that result from the global blade deformation over the entire intended duration of operation and that they have no adverse effects on the blade structure.

6.4.3 Qualification of materials for manufacture

It shall be ensured that the material types used are meeting the design assumptions with regards to the material properties specified (and any additional tests used as a basis for the design).

The manufacturer shall define a qualification scheme for minor changes and materials delivered by new suppliers. The scheme shall identify requirements and test methods used to document that material meet the design and processing properties within the values and tolerances defined in the design.

The properties include strength and stiffness as well as manufacturing processing properties or characteristics that govern the material behaviour during manufacturing process. The relation between these material properties and process parameters (time, temperature, pressure, etc.) should be established.

In case of minor changes, such as those outlined below, a reduced set of tests is permissible:

- minor adjustments in raw materials as a part of the continuous development by the material supplier or shift to a new supplier of identical materials;
- minor changes in the production process (e.g., adjustments on curing cycle).

The blade manufacturer shall have specifications, applying to laminates or raw materials (e.g., resins, adhesives, fibers) in order to define critical parameters to test during qualification.

Specifications shall include but are not limited to:

- traceability of the materials;
- repeatability of material manufacturing processes;
- verification system (e.g., test methods) of incoming material properties;
- suitable material storage conditions.

6.5 Design for manufacturing

6.5.1 General

The design shall specify in the design documentation all requirements for the manufacture, necessary to meet the technical and functional specification and achieve the assumed structural integrity of the blade, including strength, stiffness, mass, mass moment, natural frequencies and stability.

Such requirements include specific manufacturing processes, materials, dimensions, tolerances and acceptance criteria for materials, geometries and assemblies.

Material coupon samples, elements and details, sub-components or assemblies tested for definition of design values (strength, stiffness and stability) shall be representative of the as-manufactured blade.

It is the responsibility of the blade manufacturer to validate any deviations from the baseline process. The manufacturer's production process shall avoid statistically significant changes to design values established using the baseline process.

Key tolerances, processes or product characteristics and acceptance requirements shall be defined by the designer or the manufacturer as critical-to-quality parameter (CTQs); see also 6.5.2. It is required that these CTQs are measured and recorded for each production build to ensure documentation for design or process compliance.

Other tolerances, processes or product characteristics and acceptance requirements shall be considered, and compliance with design or process shown by either continued recording, monitoring or demonstrated process capabilities.

The validity of safety analysis shall extend all the way to a product that can be manufactured and within a reasonable statistical certainty, maintain the calculated safety level. This may include the definition of manufacturing tolerances without direct effect on structural calculations. To account for such effect, a minimum list of required tolerances is defined below.

6.5.2 Requirement for manufacturing tolerances

Where applicable, the list of items for which tolerances and/or acceptance criteria for manufacturing that shall be defined in the design includes, but is not limited to:

- positioning of fabrics/layup in lengthwise and chord wise direction including length, width, overlap length and overlap shifts (staggering);
- orientation of fabrics/fibers (local and global);
- fiber misalignment (including wrinkles) – in plane and out of plane;
- fiber mat area weight;
- fiber volume fraction;
- distance between ply drop – including scarf joints;
- resin processing including mixing ratio and void content;
- resin cure level and process including temperature, time and vacuum level (if applicable);
- sandwich core material positioning (gaps, misalignment);
- sandwich core material dimensions (thickness, slitting/grooves, chamfering angle);
- positioning and orientation of prefabricated parts;
- glue filling (geometry and voids);
- glue mixing ratio;

- glue free edge shape;
- glue cure level and process including temperature, time and vacuum level (if applicable);
- bond line dimensions: thickness and width as well as maximum size and extent of permissible deviation (dimensions, voids, cracks, percentage of filling/coverage);
- bonding surface preparation and protection;
- coating quality – adhesion and thickness;
- temporary storage after surface preparation, before bonding;
- bolt holes position (deviation from nominal position);
- geometric positioning of assembled parts other than bonding major structural parts (incl. balance mass). Bolted connections shall have specified pretension;
- geometric positioning and diameter of drainage hole;
- electrical resistance of lightning protection system.

6.6 Structural design

6.6.1 General design approach

Subclause 6.6 provides requirements for the analytical and numerical design of a wind turbine blade structure. The integrity of the blade structure shall be verified, and an acceptable safety level shall be demonstrated. The ultimate and fatigue strength of the blade shall be verified by calculations and/or tests.

This document describes requirements following a deterministic approach, using the limit states design method according to ISO 2394.

Alternatively, use of a reliability based design with a probabilistic approach is acceptable and could lead to other safety factors than those prescribed in this code. If a reliability-based approach is taken, the risk of failure shall be defined and documented where ISO 2394 may be used as guidance. If a reliability estimate is used instead of the factor design in this code, then the reliability model shall as a minimum account for the variability and uncertainties described in this code by the partial safety factors.

Subclause 6.6 refers to verification according to the limit states design method.

For all limit state analysis defined in IEC 61400-1, loads are defined according to the following:

$$F_\mathrm{d} = \gamma_\mathrm{f} F_\mathrm{k}$$

where

F_d is the design value for the load;

γ_f is the partial safety factor for loads;

F_k is the characteristic value for the load.

According to IEC 61400-1, the following four types of analyses shall be performed where relevant for the limit state analysis:

- analysis of ultimate strength;
- analysis of fatigue strength;
- stability analysis;
- critical deflection analysis (including mechanical interference between blade and tower, etc.).

Additionally, inter fiber failure (IFF) shall be assessed for laminate verification. For this assessment, characteristic loads, F_k, may be used (i.e. γ_f = 1,0).

Each type of analysis requires a different formulation of the limit state function and deals with different sources of uncertainties through the use of safety factors. In the following clauses, the four types of analysis are described related to wind turbine blades.

The level of modelling and verification shall be adequate for the considered failure modes, material and structural detail.

In all verification analyses, structural models shall use mean values for material stiffness (modulus). Uncertainties in modulus will be accounted for by material partial safety factors as appropriate for the analysis type.

6.6.2 Structural analysis

6.6.2.1 Ultimate strength analysis

For ultimate strength analysis, the blade structure shall be verified for all relevant failure modes using design loads. This includes but is not limited to fiber and inter-fiber failure modes.

Inter-laminar failure, delamination or de-bond failure can occur between adjacent laminae, cores or adhesives due to out-of-plane shear stresses and out-of-plane normal stresses. These failure modes will typically appear at design details such as thickness transitions, bolt connections, adhesive bond joints etc., which should be accounted for.

Sandwich core material failure can occur due to tensile, compressive, and shear loading. These failure modes should be accounted for.

6.6.2.2 Fatigue strength analysis

All fatigue strength analysis shall be done using design values for loads.

The failure mode for fatigue is the local accumulation of damage (according to the applicable fatigue damage accumulation model) in excess of that permitted by the fatigue strength of the local material during a period that is less than the design life of the structure.

Linear damage accumulation in the fiber direction according Palmgren Miner may be used to obtain the total damage. In that case, a stress or strain based constant life diagram shall be constructed from the available characteristic S-N curves. The characteristic number of cycles to failure shall be extracted for each applied strain condition (amplitude and mean level) from the constant life diagram. The number of expected cycles to failure shall be found for the applied strains/stress.

Stress or strain based verification may be replaced by fracture mechanics methods.

Fatigue calculation may be based on damage equivalent loads, Markov matrices or load time series.

Fatigue strength analysis may be based on a damage-tolerant approach:

- It shall be demonstrated that damage due to a failure mode does not otherwise compromise the structural integrity of the blade (e.g., static failure, excessive deflection, etc.) during its design life.
- When a failure mode is evaluated to be acceptable, subsequent failure modes shall be assessed. Progressive development and interaction of failure modes shall be considered.

- If a particular failure mode in the failure sequence will compromise structural integrity, then the structure shall be designed in such a way that the preceding failure mode does not lead to progression.
- The damage tolerance of a sequence of failure modes shall be verified for both static and fatigue loading conditions.
- The damage tolerance of a sequence of failure modes shall be verified by either
  - progressive damage analyses validated by intermediate level testing or full blade testing, or
  - other justified method providing the same reliability level, including testing that demonstrates the alternative load path, based on assessment of failure modes.

6.6.2.3 Stability analysis

~~Stability analyses shall include effects of both global and local stability.~~

~~Global buckling refers to loss of stability of a complete structural member or element (e.g., panel buckling) and shall be evaluated. It occurs when a small increase in load results in a large and unstable increase in deformation, thereby limiting the capacity to carry any further load.~~

~~The verification shall be based on analytical or numerical methods, full scale testing or a combination hereof.~~

~~The general design criterion for buckling is to be based on the IEC 61400-1. Primary load-carrying structures (e.g., spar caps, shear webs, trailing edge spars) shall be shown to be free of buckling when the structure is subjected to the design loads.~~

Global static instability (i.e., global buckling) occurs when a small increase in load results in a large and unstable increase in deformation, thereby limiting the capacity of the blade to carry any further load. It shall be demonstrated that global static instability does not occur at any load less than or equal to the product of the design load and the applicable combined factor of safety required herein. Nonlinear increases in the deformation of the blade in response to increases in load are permissible so long as the response remains stable, the blade does not lose its ability to carry further increases in load, and the nonlinear response does not induce damage in any structure due to other failure modes or result in excessive deflection of the blade towards the tower.

Local instability (i.e., local buckling) refers to a portion of a structural member (e.g., sandwich panel face sheet wrinkling or crimping) and shall be evaluated.

The verification of static stability shall be based on analytical or numerical methods, full scale testing or a combination hereof.

6.6.2.4 Critical deflection analysis

Deflection analysis shall be conducted according to IEC 61400-1, where also the relevant design load cases and partial safety factors are defined.

The value of γ_m for critical deflection analysis as defined in IEC 61400-1 shall be 1,1 to account for uncertainty in predicted global stiffness and blade to blade variation, if no other justification is done.

The value of γ_m may be reduced to 1,05 if the elastic properties are validated by a full scale blade test on the actual blade, the criteria of 6.6.3.2 are met without further justification, and monitoring is performed.

The value of γ_m may be reduced to values lower than 1,05 but not lower than 1,00 if the blade elastic properties consistency is demonstrated by statistics by blade deflection testing on multiple same or similar blade types indicating a better performance, and monitoring is performed.

Monitoring of elastic properties, consistent with IEC 61400-1, may be fulfilled by, but not limited to, the following methods:

- sample measurements on production components;
- testing on multiple same or similar blade types.

In all cases the value for γ_n shall be 1,0.

6.6.3 Verification requirements

6.6.3.1 Model resolution

The model used for blade structural analysis shall use as a minimum, the resolution in spanwise and chordwise directions as noted below:

- Spanwise resolution:

A sufficient number of spanwise sections shall be considered.

Verification shall include, at a minimum, 12 cross sections along the blade length (spanwise).

The spanwise distance between sections verified shall not be larger than 1 × the smallest chord length for the given section from root to largest chord.

For the sections from largest chord to 85 % of blade length the spanwise distance between sections verified shall not be larger than 2,0 × the smallest chord length for the section.

- Chordwise resolution:

A sufficiently detailed chordwise resolution shall be used for the modelling of each section. Resolution may be adapted to the verification performed.

6.6.3.2 Validation of global model by testing

~~For certification, a general validation of the design through a comparison with obtained results from full scale blade testing applies. This includes as a minimum~~ When the design created in accordance with the requirements of this document is validated through a comparison with obtained results from full scale blade testing, the following applies as a minimum:

- comparison of calculated and measured values;
- assessment of the measurement results.

Deviations of at most ± 7 % for the global bending deflection at the outermost loading station, ± 5 % for the first natural frequencies in two main directions and ± 10 % for the axial strains are permissible without further justification at load levels of the testing performed in accordance with IEC 61400-23.

6.6.3.3 Validation of analytical models and methods

Models used and assumptions made during the analytical design affect the uncertainty of calculated results.

For individual analyses, the use of partial safety factors (PSF) account for such uncertainties. Validation of numerical/analytical models for a specific design may be based on an existing comparison between numerical/analytical modelling and test results applied to comparable design concepts. The selection of partial safety factors is dependent on extent of validation of the models. Correlation to a test using longitudinal gauges only permits reduction in PSF for laminate dominated by longitudinal loading consistent with the location of the gauges. The PSF for transverse or multi-axial load dominated structures remains at the higher level. For specific analysis and selection of PSF, a validation of the corresponding models applies. For FE- or similar numerical models the limits in 6.6.3.2 may be considered as criteria for compliance.

For validation of models using an existing correlation, the blade tested and used for comparison shall be of similar design, with sufficiently representative construction and loading to the blade being designed~~ and/or certified~~.

6.6.3.4 Intermediate level tests

Intermediate-level (e.g., elements and details or sub-component level per Figure 3) or full blade testing may be used to justify reduced PSF values. Such features include, but are not limited to: wrinkles, bond-lines, embedded studs, T-bolts, and ply drops.

In addition to providing a more accurate representation of blade details than coupon tests, intermediate-level testing enables a larger number of tests than is feasible in full blade tests, thus allowing for:

- statistically relevant data sets, with additional insight in the scatter of results;
- tests under various environmental conditions;
- comparative tests of various structural solutions.

To reach the lowest PSFs, the testing should ideally be performed based on the actual boundary conditions. However, simpler boundary conditions may be used to verify modelling results and gain the required confidence in the modelling.

6.6.4 Partial safety factors for materials

6.6.4.1 Definitions

The value of the partial safety factor for materials accounts for the inherent variability and uncertainties in FRP materials, laminated sandwich structures, bonded joints, methods and load resolution. To account for this, the material factors shall be specifically developed for each material type and combination of materials. This can be done either through a reliability-based dedicated test program or through an empirical approach. When using an empirical approach, appropriate partial safety factors shall be applied as follows:

$$\gamma_{\mathrm{m}} = \gamma_{\mathrm{m0}}\ \gamma_{\mathrm{m1}}\ \gamma_{\mathrm{m2}}\ \gamma_{\mathrm{m3}}\ \gamma_{\mathrm{m4}}\quad \gamma_{\mathrm{m5}}$$

where

γ_{m0} is the “base” material factor (to be included in all analyses);

γ_{m1} is the factor for environmental degradation (non-reversible effects);

γ_{m2} is the factor for temperature effects (reversible effects);

γ_{m3} is the factor for manufacturing effects;

γ_{m4} is the factor for calculation accuracy and validation of method;

γ_{m5} is the factor for load characterization.

The combined partial safety factor for materials in this document shall not be less than the minimum partial safety factor for resistance specified in IEC 61400-1.

The designer may define an alternative empirical approach (including relevant partial safety factors), provided the approach is justified through an appropriate verification which meets an equivalent level of safety and reliability to that achieved through the approach outlined in this document.

A reliability-based test program shall cover as a minimum the variables listed by the empirical approach adopted within this document and may be based on IEC 61400-1.

Values for each of the partial safety factors for materials are given in Subclauses 6.6.4.2 through 6.6.4.7 below. A general principle is that all failure modes and associated uncertainties in the transfer of material properties to the as-built blade shall be considered in the selection. Any adjustments of the partial safety factors γ_{m0} to γ_{m5} shall be documented by the designer and ensure an overall safety and reliability of the design comparable to the use of the values given below.

6.6.4.2 γ_{m0} Base material factor

For all strength and stability analyses, the base material safety factor γ_{m0} is:

γ_{m0} = 1,20

This factor covers uncertainties not covered by other safety factors.

γ_{m0} can be reduced to a minimum of 1,0 to compensate for γ_n > 1,0 such that the product of γ_{m0} and γ_n is 1,20.

6.6.4.3 γ_{m1} Factor for environmental degradation (non-reversible effects)

The partial safety factor for environmental effects accounts for the irreversible and long term degradation of the material properties compared to initial properties. The effects may include, but are not limited to:

- long-term degradation caused by temperature variation;
- chemical ageing and degradation;
- UV radiation (if applicable);
- humidity and salinity;
- external chemical influence;
- stiffness dependence on fatigue life;
- stiffness dependence on creep or strain relaxation.

The design shall specify the relevant environmental factors for the blade. If testing is performed, the testing of materials should be designed to cover the effects of these factors. Typical testing covers combined degradation effects of extremes of temperature and moisture, or long term effects of temperature variations.

6.6.4.4 γ_{m2} Factor for temperature effects (reversible effects)

The partial safety factor for temperature accounts for reversible and short term changes in material strength and stiffness properties with varying operational temperatures and their variability and uncertainties on the base laminate properties.

6.6.4.5 γ_{m3} Factor for manufacturing effects

For all verifications, the partial safety factor for manufacturing effects accounts for strength influence from the manufacturing tolerances and uncertainties of the as-built blade relative to the idealized structure or design values based on sub component or material specimen testing.

There are three elements to demonstrating manufacturing control:

- Determination of manufacturing tolerances. These may be drawn from best industry practice or determined specifically for the structure in question based on process validation and measurements. The reduced uncertainty that results from representative trials is reflected in the resulting PSF.
- Control of manufacturing CTQs. Specification during the design process of manufacturing CTQs that are measured and recorded for each production build results in reduced uncertainty. This includes material qualification and on receipt inspection.
- Material performance at tolerance limits. Characterization of the material and representative substructure performance at the limits of specified tolerances results in greatly reduced uncertainty. This is reflected in the PSF.

Tolerance stack-up shall be interpreted as the properties of the material at the limits of all the tolerances, not the product of individual knock-downs.

The analysis of manufacturing effects shall take into consideration the confidence level of the associated:

- inspection methods;
- manufacturing controls;
- manufacturing experience when documented by measurable process capabilities

(duration, conditions, protection).

GUIDANCE – Variation impact analysis

This guidance section makes provision for the evaluation of identified critical manufacturing process robustness and repeatability within the blade design assessment.

For the determination of the level of γ_{m3}, the designer should specify the allowable tolerances in the critical manufacturing processes for a particular component or assembly and quantify their effects on the design properties.

This may require one, or a combination of more than one of the dominant tolerances to be considered.

In determination of the dominant tolerance for a particular manufacturing process, the designer should assess:

- likely variations (and magnitude thereof) to manufacturing process;
- detectability of variations;
- structural performance reduction due to variations.

If the designer wishes to adopt the lowest level of γ_{m3}, then verification of the structural performance shall be performed using a test program to determine material properties.

The test program shall utilize samples which embody maximum variations identified in the process assessment and loading regimes which represent the critical design conditions. It is not mandatory to verify by test the effect of every tolerance if there is sufficient evidence that some are not significant or can be assessed by analysis.

The analytical methods-based approach shall account for maximum variations identified in the process assessment and loading regimes which represent the critical design conditions. It is not mandatory to quantify the effect of every tolerance if there is sufficient evidence that some are not significant.

Table 1 below may be used as a template for identifying typical manufacturing effects (γ_{m3}) in relation to specific structural design verifications.

Table 1 – Typical manufacturing effects

Type of manufacturing tolerance to be evaluated: **for the verifications:**	**Fiber misalignment / orientation / wrinkles**	**Fiber volume fraction**	**Void content**	**Degree of cure / T_g** **Resin mixing ratio**	**Positioning (gaps, overlaps)**	**Bonding surface preparation and protection**	**Bond line thickness**	**Adhesive free edge shape**	**Adhesive open time**	
Laminate ultimate strength										
Laminate fatigue strength										
Inter fiber failure										
Sandwich core ultimate strength										
Global buckling										
Local buckling										
Bond ultimate strength										
Bond fatigue strength										
Mechanical fastening (ultimate and fatigue strength)										
Non-structural features										

END OF GUIDANCE

6.6.4.6 γ_{m4} Factor for calculation accuracy and validation of method

The partial safety factor for calculation methodology shall account for uncertainties related to the analysis methods used. The safety factor shall consider the accuracy of the analysis and the thoroughness of its verification.

In the case of laminate fatigue assessment, two components are considered in the factor for calculation and validation:

γ_{m4} is the product of γ_{m4a} and γ_{m4b}:

- γ_{m4a} factor for model validation: Correlation of predictive models used reduces uncertainty in the design.
- γ_{m4b} factor for fatigue model: Utilization of material fatigue properties supported by fatigue testing and more sophisticated damage accumulation models reduces uncertainty.

6.6.4.7 γ_{m5} Factor for load characterization

This partial safety factor accounts for uncertainties related to the resolution of, and combination of relevant applied load components.

In the simplest case, loads resolved into the positive and negative extremes of two perpendicular directions (e.g., minimum and maximum flatwise and minimum and maximum edgewise) for a total of four load sets may be applied individually.

Blade analysis incorporating intermediate load directions and combined loading events provide better representation and therefore justify lower partial safety factors.

In the case of laminate fatigue assessment, two components are considered in the factor for resolution of load components:

γ_{m5} is the product of γ_{m5a} and γ_{m5b}:

- γ_{m5a} is the factor for load direction resolution;
- γ_{m5b} is the factor for fatigue load formulation.

6.6.5 Structural design verification

6.6.5.1 Verification requirements

The following structural verifications shall be performed:

Laminate verification:

- laminate ultimate strength;
- laminate fatigue strength;
- inter fiber failure;
- sandwich core ultimate strength.

Stability verification:

- global buckling;
- local buckling.

Bonded joint verification:

- bond calculation ultimate strength;
- bond calculation fatigue strength.

Components:

- mechanical fastening ultimate and fatigue strength;
- non-structural features.

The detailed description of these verifications can be found in Subclauses 6.6.5.2 through 6.6.5.11.

6.6.5.2 Laminate ultimate strength verification

Factor	Values
γ_{m1}	**Factor for environmental degradation (non-reversible effects)** 1,20 – Material properties are based on room temperature, dry mechanical properties 1,00 – Material properties that take into account the relevant effects of environmental degradation
γ_{m2}	**Factor for temperature effects (reversible effects)** 1,10 – Material properties are based on room temperature 1,00 – Material properties tested to cover the extremes of the operational temperature range
γ_{m3}	**Factor for manufacturing effects** 1,30 – The blade analysis is performed using nominal design properties. The effect of dominant manufacturing tolerances on the design properties has been considered and shown appropriate within the safety factor used. 1,10 – The blade analysis is performed using design properties that include the quantified effect of the dominant manufacturing tolerances. The effect of these tolerances on the design properties has been verified by analytical methods and/or literature reference where applicable. 1,00 – The blade analysis is performed using design properties that include the verified effect of the dominant manufacturing tolerances based on process validation and measurements. The effect of these tolerances, including tolerance stacking, on the design properties have been verified by testing. In the case of wrinkles and ply drops, intermediate-level or full blade testing shall be used.
γ_{m4}	**Factor for calculation accuracy and validation of method** 1,20 – Strain calculation not validated 1,00 – Strain calculation validated by full blade test
γ_{m5}	Factor for load characterization 1,20 – Loads in 4 main directions 1,00 – Minimum 12 evenly distributed load directions

6.6.5.3 Laminate fatigue strength verification

Factor	Values
γ_{m1}	**Factor for environmental degradation (non-reversible effects)** 1,10 – Material properties are based on room temperature, dry mechanical properties 1,00 – Material properties that take into account the relevant effects of environmental degradation
γ_{m2}	**Factor for temperature effects (reversible effects)** 1,00 – No effect accounted for
γ_{m3}	**Factor for manufacturing effects** 1,30 – The blade analysis is performed using nominal design properties. The effect of dominant manufacturing tolerances on the design properties has been considered and shown appropriate within the safety factor used. 1,10 – The blade analysis is performed using design properties that include the quantified effect of the dominant manufacturing tolerances. The effect of these tolerances on the design properties has been verified by analytical methods and/or literature reference where applicable. 1,00 – The blade analysis is performed using design properties that include the verified effect of the dominant manufacturing tolerances based on process validation and measurements. The effect of these tolerances, including tolerance stacking, on the design properties have been verified by testing. In the case of wrinkles and ply drops, intermediate-level or full blade testing shall be used.
γ_{m4}	**Factor for calculation accuracy and validation of method** γ_{m4a}: Model (strain response to loads) validation 1,20 – Strain calculation not validated 1,00 – Strain calculation validated by full blade test γ_{m4b}: Fatigue model (Goodman or equivalent), based upon 1,20 – static strength and assumed Wöhler slope 1,10 – static strength and minimum one measured Wöhler slope 1,00 – full fatigue characterization (see 6.4.2.2) γ_{m4} is the product of γ_{m4a} and γ_{m4b}.

Factor	Values
γ_{m5}	**Factor for load characterization** γ_{m5a}: Factor for load direction resolution 1,20 – Bending moment spectrum evaluated on two main directions 1,00 – Bending moment spectrum evaluated on a minimum of six directions or strain spectrum evaluated from exact strain history (from time series) γ_{m5b}: Factor for fatigue load formulation 1,20 – Use of damage equivalent loads 1,00 – Use of full fatigue load description by e.g. Markov Matrix, time series γ_{m5} is the product of γ_{m5a} and γ_{m5b}

6.6.5.4 Inter fiber failure

Inter fiber failure (IFF) modes shall be considered for laminate and sandwich structures, based on characteristic loads F_k.

IFF can lead to subsequent premature fiber failure (both static and fatigue), as well as premature buckling failure.

Failure modes to be considered include IFF caused by in-plane transversal tensile or compressive stresses (σ_2), by in-plane shear stresses (τ_{12}), or a combination of these, and also as influenced by in-plane longitudinal tensile or compressive stresses (σ_1).

It shall be shown, by suitable means of verification that sufficient safety against the effects of IFF exists.

A suitable verification can consist of one or a combination of the three following:

1) Demonstration by analysis that matrix cracking does not occur for each individual layer of laminate

   The actual safety shall be documented in the analysis for ultimate strength by a failure hypothesis for anisotropic materials that is acknowledged in the literature, e.g., as per VDI 2014, Puck or Larc03. If a failure hypothesis as mentioned above is used, unless otherwise documented, the coefficients shall be included as follows:

$$p_{4\parallel}\ (-) = 0,25$$

$$p_{4\parallel}\ (+) = 0,3$$

   where $p_{4\parallel}$ (-) and $p_{4\parallel}$ (+) are the inclination parameters according to Puck.

   For the analytical verification, strength and strain design limits shall be based on average values from material testing.

Factor	Values
γ_{m1}	**Factor for environmental degradation (non-reversible effects)** 1,00 – No effect accounted for
γ_{m2}	**Factor for temperature effects (reversible effects)** 1,10 – For calculation performed by models using mean material modulus values valid for room temperature 1,00 – For calculations performed using mean material modulus values valid for the lowest operational temperature
γ_{m3}	**Factor for manufacturing effects** 1,10 – To be used for all analyses
γ_{m4}	**Factor for calculation accuracy and validation of method** 1,10 – For finite element (FE) analysis 1,20 – For other analytical models
γ_{m5}	**Factor for load characterization** 1,10 – Loads in 4 main directions 1,00 – Minimum 12 evenly distributed load directions

2) Demonstrate by analysis that matrix cracking is not critical to structural integrity

   Perform verification for laminate ultimate strength (see 6.6.5), laminate fatigue strength (see 6.6.5.3) and global stability (see 6.6.5.6) using design properties taking into account pre-damage by matrix cracking. This requires that all relevant material design limits are established through test coupons that have been subjected to load-induced matrix cracking prior to ultimate or fatigue failure test.

   The material test programme shall at least include, but not be limited to, the following:

   - UD and multiaxial fabrics ultimate tensile and compression with pre-damage induced by in-plane transversal tension and/or in-plane shear;
   - UD and multiaxial fabrics fatigue with pre-damage induced by in-plane transversal tension and/or in-plane shear.

   The pre-loading shall at a minimum be equivalent to the design ultimate strain or stress for the relevant material and direction.

3) Successful full blade test

   This test shall as a minimum include pre-fatigue static tests, fatigue tests and post-fatigue static tests according to IEC 61400-23.

   It shall be justified by analysis or other technical argumentation that areas with matrix cracking being a potential failure mode are sufficiently loaded.

   Inter fiber failures may be acceptable if these failure modes are understood and do not cause exceedance of other limit states.

6.6.5.5 Sandwich core ultimate strength verification

For ultimate strength verification of sandwich cores, the product of γ_{m0} and the factors γ_{m1} through γ_{m5} listed below shall be applied to the core material ~~mean~~ statistically derived characteristic strength values. The strength of the core material shall be demonstrated with respect to, but not limited to, minimum out-of-plane shear and crushing (i.e., compression normal the face sheets). In assessing the strength, local nonlinear deformations due to face sheet buckling shall be considered if appropriate.

Factor	**Values**
γ_{m1}	**Factor for environmental degradation (non-reversible effects)** 1,30 – Open cell foams, wood and honeycombs (allows ingress to core laminate interface due to temp variations) for which the material properties are based on room temperature 1,10 – Closed cell foams, wood and open cell foams with resin infusion for which the material properties are based on room temperature 1,00 – Material properties that take into account the relevant effects of environmental degradation
γ_{m2}	**Factor for temperature effects (reversible effects)** 1,20 – Material properties are based on existing literature or data sheets only 1,10 – Material testing is performed at room temperature 1,00 – Material properties tested to cover the extremes of the operational temperature range.
γ_{m3}	**Factor for manufacturing effects** 1,30 – The blade analysis is performed using nominal design properties. The effect of dominant manufacturing tolerances on the design properties has been considered and shown appropriate within the safety factor used. 1,10 – The blade analysis is performed using design properties that include the quantified effect of the dominant manufacturing tolerances. The effect of these tolerances on the design properties has been verified by analytical methods and/or literature reference where applicable. 1,00 – The blade analysis is performed using design properties that include the verified effect of the dominant manufacturing tolerances based on process validation and measurements. The effect of these tolerances, including tolerance stacking, on the design properties have been verified by testing. In the case of wrinkles and ply drops, intermediate-level or full blade testing shall be used.

Factor	Values
γ_{m4}	**Factor for calculation accuracy and validation of method** 1,35 – For analytical methods based on assumed or manufacturer's unsubstantiated data and that have not been validated by intermediate-level or full blade testing. 1,20 – For finite element analysis based approaches using shell elements for panels combined with analytical expression for core strength failure mode, and the method of which has not been validated by intermediate-level or full blade testing. 1,20 – For computation using a finite element analysis using 3D elements for the core and that models geometric nonlinearities but that has not been validated by intermediate-level or full blade testing. 1,00 – For finite element analysis based approaches using shell elements for panels combined with analytical expression for core strength failure mode, the method of which has been validated by intermediate-level or full blade testing. 1,00 – For computation using a finite element analysis using 3D elements for the core and that models geometric nonlinearities, the method of which has been validated by intermediate-level or full blade testing.
γ_{m5}	**Factor for load characterization** 1,20 – Loads in 4 main directions 1,00 – Minimum 12 evenly distributed load directions

6.6.5.6 Global static stability (global buckling)

The designer shall verify through analysis that the blade does not lose its ability to carry load due to static instability at the design load with a combined safety factor equal to the product of γ_{m0} and the factors γ_{m1} through γ_{m5} listed in the table below.

The analyses shall be ~~conducted~~ based on using statistically derived mean values of the material stiffness.

Thicknesses of sandwich cores shall be conservatively estimated, including potential compression related to the selected method of manufacturing.

The suitability of the FE mesh density shall be demonstrated by a convergence study. A sufficient accuracy of the mesh may be assumed when the (linear) buckling eigenvalue does not change by more than 5 % if the mesh density is doubled in the region of the model pertinent to the buckling mode in question.

~~For geometric non-linear FE-analyses, the load vector directions shall be considered and related to the deformation of the blade and consistent with the external loading. A stress-free pre-deformation proportional to the relevant linear buckling eigenforms shall be applied to the structure with an appropriate scaling of the height. In the absence of further justification (e.g., geometric imperfections related to production tolerances), the height of the imperfection shall be 0,25 % of the relevant eigenform wavelength.~~

~~Stable post-buckling behavior is permitted under the following conditions:~~

- ~~Buckling shall not result in failure of any structural members at the design load. All relevant failure modes shall be examined in the buckled condition, as per the remaining requirements of this document.~~
- ~~Buckling shall not occur at a load low enough to result in local fatigue damage, as per requirements elsewhere in this document.~~
- ~~Buckling shall not result in excessive deflection of the blade as defined elsewhere in this document.~~

For verification using linear methods of buckling analysis, it shall be demonstrated that the minimum eigenvalue corresponding to the first eigenform exceeds the required combined safety factor.

For verification using finite element analyses that model geometric non-linearity:

- The analysis shall demonstrate convergence when the combined safety factor γ_m has been applied to the design load.
- The load vector directions shall be considered and related to the deformation of the blade and consistent with the external loading.
- The FEM shall accurately reflect geometric imperfections related to validated production tolerance data. Alternatively, in the absence of validated production tolerance data, a stress-free pre-deformation proportional to the relevant linear buckling eigenforms (i.e., linear modes with an eigenvalue less than the required combined safety factor, including γ_m4a = 1,20) shall be applied to the structure with the height scaled to 0,25 % of the relevant eigenform wavelength. For the non-linear analysis in each load direction, a single pre-deformation may be formed from the superposition of the pre-deformations for the pertinent eigenforms associated with each independent linear buckling mode that does not fulfil the criteria for verification of static stability using a linear buckling calculation in that load direction.
- Nonlinear response shall not
  - result in failure of any structural member; all relevant failure modes shall be examined as per the remaining requirements of this document, appropriately accounting for nonlinear response;
  - occur at a load low enough to result in local fatigue damage, as per requirements elsewhere in this document;
  - result in excessive deflection of the blade as defined elsewhere in this document.

The term "independent linear buckling mode" is used to distinguish between buckling modes that appear at different locations on a blade and are due to distinctly different structural responses of the blade to a given externally applied load, in contrast to multiple modes emanating from a single location on the blade and reflective of a common structural response of the blade to the applied load. For example, in Figure 6, modes 1, 2, and 3 would be considered non-independent modes, while modes 1 and 20 would be considered independent of each other. The pertinent eigenforms that are included in the definition of the pre-deformation for each independent mode shall be selected to ensure that the full extent of the linear modes is addressed while ensuring that modes do not partly compensate for each other. If independent modes occur near each other, higher modes of each can overlap in a way that can obscure the independent nature.

Alternatively, the eigenforms associated with each independent linear buckling mode may be considered individually.

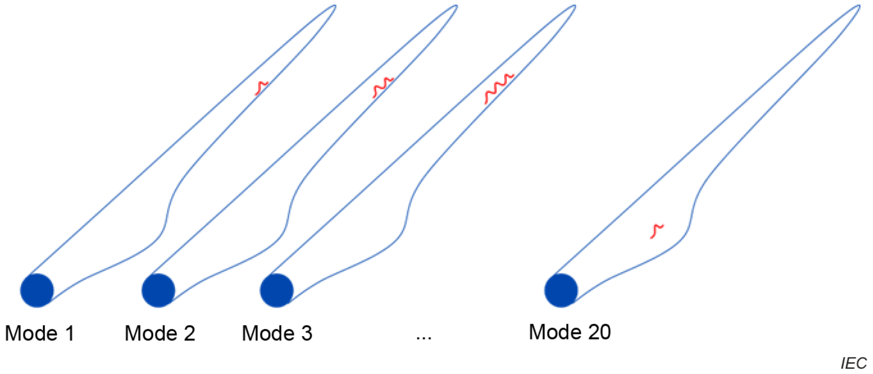

Figure 6 – Examples of Independent and non-independent linear buckling modes

Alternatively, the static stability of the blade may be verified through full scale testing. The test load used for verification shall equal the product of the design load and a combined safety factor equal to γ_m = 1,6.

Factor	Values
γ_{m1}	**Factor for environmental degradation (non-reversible effects)** 1,00 – No effect accounted for
γ_{m2}	**Factor for temperature effects (reversible effects)** 1,10 – When using core material modulus values at room temperature 1,00 – When using core material modulus values taking into account the highest operating temperature
γ_{m3}	**Factor for manufacturing effects** 1,00 – No effect accounted for
γ_{m4}	**Factor for calculation accuracy and validation of method** γ_{m4a}: Factor for analytical method 1,40 – For two-dimensional analytical methods (non FEA) 1,20 – For linear finite element analysis methods 1,00 – For computation using a finite element analysis that models geometric nonlinearities γ_{m4b}: Factor for validation 1,25 – For no validation 1,00 – For methods of which has been validated by intermediate level or full blade testing to non-linear buckling detection or failure γ_{m4} is the product of γ_{m4a} and γ_{m4b}.
γ_{m5}	**Factor for load characterization** 1,20 – Loads in 4 main directions 1,00 – Minimum 12 evenly distributed load directions

6.6.5.7 Local stability verification (face sheet buckling)

The analyses shall be conducted using mean values of the material stiffness.

For the static stability analysis, the partial safety factor γ_{m2} listed below may be applied to the material stiffness or to the load.

Nonlinear deformations that are stable are permissible so long as the deformations do not result in

- local static failure of either the face sheets or the core;
- delamination of the face sheets from the core;
- fatigue damage.

Factor	Values
γ_{m1}	**Factor for environmental degradation (non-reversible effects)** 1,00 – No effect accounted for
γ_{m2}	**Factor for temperature effects (reversible effects)** 1,10 – When using core material modulus values at room temperature 1,00 – When using core material modulus values taking into account the highest operating temperature
γ_{m3}	**Factor for manufacturing effects** 1,00 – No effect accounted for
γ_{m4}	**Factor for calculation accuracy and validation of method** 1,35 – For analytical methods based on assumed or manufacturer's unsubstantiated data and that have not been validated by intermediate-level or full blade testing. 1,20 – For finite element analysis based approaches using shell elements for panels combined with analytical expression for core strength and face sheet wrinkling failure modes, and not supported by validation testing. 1,20 – For computation using a finite element analysis using 3D elements for the core and that models geometric nonlinearities but that has not been validated by intermediate-level or full blade testing. 1,00 – For finite element analysis based approaches using shell elements for panels combined with analytical expression for core strength and face sheet wrinkling failure modes, the method of which has been validated by intermediate-level or full blade testing. 1,00 – For computation using a finite element analysis using 3D elements for the core and that models geometric nonlinearities, the method of which has been validated by intermediate-level or full blade testing.
γ_{m5}	**Factor for load characterization** 1,20 – Loads in 4 main directions 1,00 – Minimum 12 evenly distributed load directions

6.6.5.8 Bonded joint ultimate strength verification

This Subclause 6.6.5.8 covers the verification of the bonded joints for the ultimate strength state.

Design assessment of ultimate strength of bonded joints shall consider principal features of the joints such as the adhesive, bond line interface and inter-laminar loading of the adjacent substrate material and geometry. Features subject to inter-laminar loading not associated with a bonded joint shall also be handled in this Subclause 6.6.5.8. Adhesive joints comprising dissimilar substrates, such as composite to metal interfaces, shall also be handled with this Subclause 6.6.5.8.

Factor	Values
γ_{m1}	**Factor for environmental degradation (non-reversible effects)** 1,20 – Material properties are based on room temperature, dry mechanical properties 1,00 – Material properties that take into account the relevant effects of environmental degradation
γ_{m2}	**Factor for temperature effects (reversible effects)** 1,10 – Material properties tested at room temperature 1,00 – Material properties tested to cover the extremes of the operational temperature range
γ_{m3}	**Factor for manufacturing effects** 1,30 – The blade analysis is performed using nominal design properties. The effect of dominant manufacturing tolerances on the design properties has been considered and shown appropriate within the safety factor used. 1,10 – The blade analysis is performed using design properties that include the quantified effect of the dominant manufacturing tolerances. The effect of these tolerances on the design properties has been verified by analytical methods and/or literature reference where applicable. 1,00 – The blade analysis is performed using design properties that include the verified effect of the dominant manufacturing tolerances based on process validation and measurements. The effect of these tolerances, including tolerance stacking, on the design properties have been verified by testing.

Factor	Values
γ_{m4}	**Factor for calculation accuracy and validation of method** 2,00 – Analytical methods utilizing an average stress based failure criteria are employed to predict structure load carrying capability. The failure criteria used shall be based on the average bond stress of representative tests. Representative tests means similar interface materials, substrates and loading. 1,30 – A finite element model with stress based failure criteria is employed to predict structure load carrying capability. The model and failure criteria used shall be validated by representative tests. Representative tests means similar interface materials, geometry, model mesh refinement and ratio of peel and shear. 1,10 – A finite element model with fracture mechanics based failure criteria (such as interface elements or other analytical method) is employed to predict structure load carrying capability. Predictive capability shall be validated by representative intermediate-level or full blade tests. Representative tests means similar interface materials and ratio of peel and shear. Material properties shall be determined through suitable material tests. 1,00 – The characteristic strength for the as-manufactured bonding or detail has been established through an intermediate-level or full blade test performed such that the structure and loading are representative of the part being designed. It shall be shown by finite element analysis or similar method that the loading on the blade detail is lower or equal to the tested structures' characteristic strength with PSF applied.
γ_{m5}	**Factor for load characterization** 1,00 – No effect accounted for

6.6.5.9 Bonded joint fatigue strength verification

This Subclause 6.6.5.9 covers the verification of the bonded joints for the fatigue failure state.

Design assessment of fatigue strength of bonded joints shall consider principal features of the joints such as the adhesive, bond line interface and interlaminar loading of the adjacent substrate material and geometry. Features subject to inter-laminar loading not associated with a bonded joint shall also be handled in this Subclause 6.6.5.9. Adhesive joints comprising dissimilar substrates, such as composite to metal interfaces, shall also be handled with this subclause.

Factor	Values
γ_{m1}	**Factor for environmental degradation (non-reversible effects)** 1,10 – Material properties are based on room temperature, dry mechanical properties 1,00 – Material properties that take into account the relevant effects of environmental degradation
γ_{m2}	**Factor for temperature effects (reversible effects)** 1,00 – No effect accounted for
γ_{m3}	**Factor for manufacturing effects** 1,30 – The blade analysis is performed using nominal design properties. The effect of dominant manufacturing tolerances on the design properties has been considered and shown appropriate within the safety factor used. 1,10 – The blade analysis is performed using design properties that include the design effect of the dominant manufacturing tolerances. The effect of these tolerances on the design properties has been verified by analytical methods and/or literature reference where applicable. 1,00 – The blade analysis is performed using design properties that include the verified effect of the dominant manufacturing tolerances based on process validation and measurements. The effect of these tolerances, including tolerance stacking, on the design properties have been verified by testing.
γ_{m4}	**Factor for calculation accuracy and validation of method** 2,00 – Analytical methods utilizing an average stress based failure criteria are employed to predict structure load carrying capability. The failure criteria used shall be based on the average bond stress of representative tests. Representative tests means similar interface materials, substrates and loading. 1,30 – A finite element model with stress based failure criteria is employed to predict structure load carrying capability. The model and failure criteria used shall be validated by representative tests. Representative tests means similar interface materials, geometry, model mesh refinement and ratio of peel and shear. 1,10 – A finite element model with fracture mechanics based failure criteria (such as interface elements or other analytical method) is employed to predict structure load carrying capability. Predictive capability shall be validated by representative intermediate-level or full blade tests. Representative tests means similar interface materials and ratio of peel and shear. Material properties shall be determined through suitable material tests. 1,00 – The characteristic strength for the as-manufactured bonding or detail has been established through an intermediate-level or full blade test performed such that the structure and loading are representative of the part being designed. It shall be shown by finite element analysis or similar method that the loading on the blade detail is lower or equal to the tested structures' characteristic strength with PSF applied.

Factor	Values
γ_{m5}	**Factor for load characterization** 1,05 – Use of damage equivalent loads 1,00 – Use of full fatigue load description by e.g. Markov Matrix, time series

6.6.5.10 Mechanically fastened structural interfaces

6.6.5.10.1 General

Structural interfaces are connections between the wind turbine blade and distinct structural components such as the rotor hub structure, tip brake mechanisms, control surfaces or connections within the blade to facilitate a multi-part blade structure. These interfaces are usually comprised of two distinct materials (e.g., the composite blade structure and metal mechanical systems) that are joined using mechanical fasteners such as bolts or rivets.

For joints that rely on the combined effect of mechanical fastening and adhesion, each of the fastening methods shall be verified individually unless the load carrying capability of the combined system is demonstrated. Computational models of such interfaces may be validated through intermediate-level or full blade testing.

Strength verification of the structural interface may consider the following as a minimum:

- ultimate limit states;
- fatigue limit states.

Verification of interfaces shall account for the flexibility of the entire joint, including the fasteners and attached relevant structural components. Evaluation of pre-tensioned joints shall consider the potential for opening of gaps between the joined components. In situations where the thickness of the laminate is such that assumptions of plane strain/stress are not appropriate, the full 3D state of strain/stress shall be considered.

Strength verification of the mechanically fastened interface shall account for stress concentrations around holes in the surrounding material. Verification of the mechanically fastened interface shall furthermore consider the influence of specified tolerances on manufacturing and assembly (e.g., hole diameters, interface mating, tensioning and torqueing of fasteners, etc.). Verification of preloaded joints shall consider the long-term influences of stress relaxation and creep.

6.6.5.10.2 Blade root structure

The blade root structure where it interfaces with the rotor hub structure shall be analyzed using the same approaches defined for static strength, IFF, fatigue and adhesive bonds. However, special considerations shall be made to account for the influence of thick laminate and three-dimensional effects for which classical (thin) laminate analyses is not applicable. Furthermore, special attention to inter-laminar shear due to cleavage, wedge and other three-dimensional effects shall be considered. The complexity of the blade root end requires full blade and/or sub-component tests to determine the critical failure modes.

Tests shall be designed to capture the relevant failure modes for ultimate and fatigue strength. The geometry of the surrounding laminates shall be representative for the blade root connection. The test load levels shall be representative for the blade design.

Fatigue tests shall represent load introduction and load levels relevant for the blade design(s). Scaling of geometry and load cycles shall be verified and reported in the design documentation. Interpolation of test results to different geometries of the insert (e.g., diameter, length) shall be justified.

6.6.5.11 Non-structural features

Non-structural features are defined as items not directly contributing or affecting the load-carrying part of the blade, for example elements of the lightning protection system, anchor points (for fall arrest systems), aerodynamic devices (vortex generators, etc.), non-structural bulkheads and measurements systems.

Non-structural features do not include blade root interfaces, blade shell, web and spar structure, etc.

Where the failure of a non-structural feature can result in a safety risk for persons or property, a strength analysis shall be performed.

Verification methods and partial safety factors may be selected based on individual assessments, including considerations for safety for persons and property.

For all strength analyses, the minimum partial safety factor γ_m is:

$\gamma_m = 1,20$

6.6.6 Additional failure modes

6.6.6.1 Lightning

Wind turbine blades shall be designed against lightning strikes through the installation of a lightning protection system. The lightning protection system shall meet the requirements of IEC 61400-24.

6.6.6.2 Erosion

Wind turbine blades are vulnerable to erosion, in particular at the leading edge and tip. This erosion can be caused by environmental exposure such as rain, dust, and sand.

Relevant surface finishes should be evaluated for expected erosion, and the basis for erosion protection is to be specified for the blade.

If the blade utilizes anti-icing functions, the surface finishes should be evaluated against erosion for the maximum expected surface temperatures.

6.6.6.3 Other environmental effects

FRP materials are commonly sensitive to the direct exposures to external environmental effects such as moisture, foreign chemicals, and UV radiation. The blade design shall ensure that the structure is protected from these effects with an adequate environmental sealing system.

Materials should be selected that do not decompose chemically in the expected environment during the design lifetime. If this cannot be avoided, these effects should be quantified and considered in the development of the material's characteristic strength.

The inadvertent exposure of materials to chemicals (such as hydraulic fluid) during maintenance activities should also be considered. If the exposure is considered significant, its effects should be considered in the development of characteristic strengths.

Some core materials may release gases over time, especially under high temperatures. The pressure build-up from these gases can cause core/skin delamination. This should be considered.

Corrosion of the constituent materials shall also be considered. Carbon fiber materials in contact with metals can lead to galvanic corrosion and the effects shall be considered.

Provision shall be made for the prevention of water accumulation in the blade.

7 Manufacturing requirements

7.1 Manufacturing process

The manufacturing process shall be suitable to meet the requirements defined in the structural design.

A risk assessment for each production step should be prepared (e.g., PFMEA process failure mode and effect analysis) including the effects of tolerances and acceptance criteria and their compliance with the structural design assumptions.

Critical and significant process parameters shall be identified. These shall be documented in a control plan or equivalent.

A process specification shall be established, including at least the following:

- description of successive manufacturing steps;
- description of successive quality control steps.

For each manufacturing step, a work instruction shall be established, including at least the following:

- detailed description of each action to be carried out, including sketches or photos if necessary;
- manufacturing drawings, clearly indicating dimensions, positions, and tolerances, for all individual elements (such as fiber material plies, or bond lines);
- materials to be used (bill of material);
- equipment and tools to be used.

A change management system shall be established to control, document and assure appropriate engineering evaluation of changes implemented in design, process and tooling specifications.

In Subclauses 7.2 through 7.8, required CTQs and requirements for process measurements and recordings are stated. Definitions of these are found in 6.5.1.

7.2 Workshop requirements

7.2.1 General

Manufacturers shall be suitable for the work to be carried out with respect to their workshop facilities, manufacturing processes, tools and equipment, as well as training and capabilities of the personnel.

Proof of this may be provided by means of a documented quality management system.

~~It is the responsibility of the manufacturer to observe and conform to the manufacturing requirements defined in this document, to national laws and regulations, including health and safety regulations, other technical standards where applicable, storage and processing requirements for material and operator requirements for tools and equipment.~~

Where the requirements in this document will not ensure repeatability and product compliance with the design, necessary requirements shall be specified in the quality management system.

7.2.2 Workshop facilities

Workshop facilities shall be suitable for the work to be carried out.

~~All workshops and their operational equipment shall meet the requirements of the national laws, regulations and standards.~~

Environmental requirements shall be defined for all areas where material processing or storage takes place. These requirements shall be monitored and recorded by local measurements.

For laminating workshops, if no other temperature and humidity values have been defined and documented as acceptable for the manufacturing process, a shop room temperature between 16 °C and 30 °C with a maximum relative humidity (RH) between 20 % and 80 % RH shall be maintained when materials are exposed to atmosphere. If the manufacturers of the laminating resins or adhesives have specified other processing temperatures and humidity, these should apply.

The provision of ventilation supply and exhaust equipment shall be such that an impairment of the materials is excluded, e.g., no unacceptable amounts of solvent are extracted from the laminate.

The danger of contamination of materials for laminating shall be kept to a minimum by separation of production areas and other workshops as well as storage rooms.

The workplaces shall be illuminated in a suitable manner. Precautionary measures shall be taken to prevent the uncontrolled curing of the resin due to illumination.

For specific work processes additional requirements may apply, and shall be stated.

As a minimum, the following CTQs shall be specified and recorded:

- shop room temperature and humidity shall be recorded continuously, according to QM specifications.

7.2.3 Material handling and storage facilities

Reactive materials, such as laminating resin compounds, prepregs, gelcoat, paint and adhesives shall be transported and stored according to the manufacturer’s instructions. The temperature and humidity in the storage and process areas shall be recorded continuously.

Reinforcing materials, core materials, fillers and additives shall be stored in closed packages, in such a way that contamination and environmental degradation (e.g., caused by dust, temperature, humidity, etc.) is prevented. Moisture sensitive materials exposed to air humidity shall be stored in spaces with continuous moisture recordings and humidity shall not exceed limitations specified for such materials unless the effect of such exceedance is insignificant.

Storage shall be arranged in such a way that the designation of the materials and the storage conditions and maximum storage periods (expiration dates) prescribed by the manufacturer, are easily visible. Materials whose shelf life has been exceeded shall be marked as being out of conformity and prohibited for use, unless proven and documented that the material is fit for specific purpose.

All materials sensitive to humidity to be processed shall remain with the packaging sealed when brought to the processing rooms, until their temperature will prevent condensation (reaching the dew point).

Reactive and moisture sensitive materials stored in packages removed from storage and opened may be returned to storage only in defined cases (e.g., hot-curing prepregs). The packages have to be clearly designated in such case.

Storage and handling of all materials (including auxiliary materials) which may have an impact to quality of any component should be considered.

7.2.4 Tools and equipment

7.2.4.1 Moulds and tooling

Molds and tooling equipment shall be suitable for the manufacturing process used.

Molds and tooling that provide final geometry of the blade shall be validated for compliance with functional requirements.

This includes, but is not limited to:

- temperature distribution during process (if applicable);
- surface roughness;
- surface waviness;
- geometry including tolerances.

7.2.4.2 Maintenance

A maintenance plan shall be defined for all tools, molds and equipment (excluding generic hand tools, etc.).

The maintenance plan shall specify by time intervals, process cycles or equivalent valid definitions for inspections and acceptance criteria.

In order to trace inspection/maintenance, tools and equipment that shall be marked with unique identification includes, but is not limited to (if applicable):

- all molds for laminating work;
- automatic process equipment for mixing liquid raw materials;
- drilling machine for blade connection;
- assembly jigs and fixtures.

The process for maintenance shall be described in the QM system.

7.2.4.3 Calibration

Measurement equipment used in the manufacturing process, including mixing equipment (e.g., flow measurement devices) for liquid raw materials, shall be subject to scheduled calibration.

The list of measurement equipment to be subject to scheduled calibration includes, but is not limited to:

- temperature and humidity sensors;
- dimension and angle measuring equipment (e.g., calipers, tape measure, laser measure);
- pressure sensors (if critical to process);
- mass measuring equipment (e.g., scales/load cells);
- dispensers/flow sensors.

Equipment shall be marked with a traceable label which includes the next required calibration date.

The process for calibration shall be described in the QM system.

7.2.5 Personnel

7.2.5.1 Training and qualification

The personnel assigned to blade manufacturing shall be sufficiently qualified.

Personnel performing or controlling critical work processes that directly or indirectly are influencing the structural integrity, including material properties, shall be qualified for such work.

Training and competence requirements for critical processes shall be defined.

Critical processes are defined as, but are not limited to:

- lay up of fiber reinforcement material, including prepregs;
- lay up of sandwich core materials;
- lay up of wood parts;
- installation of sub components;
- application of resin and glue;
- manual mixing of two or multiple component materials;
- application of gelcoat or paint;
- cutting, drilling or grinding structural materials;
- welding;
- NDT processes;
- QC including visual inspections.

Training level and competencies shall be documented for each employee performing or controlling critical work processes and be subject to regular reviews in accordance to the manufacturer’s quality management system.

~~7.2.5.2 Environment, health and safety~~

~~This document does not cover requirements for environment, health and safety. Reference to national and local laws and requirement are to be observed.~~

~~The fabrication of laminates may involve certain health risks, a health and safety plan should be in place that describes how to deal with:~~

- ~~hazardous materials;~~
- ~~hazardous processes;~~
- ~~training of personnel;~~

- ~~use of personal protection equipment.~~

~~Personal protection equipment and material safety data sheets should be available and used to meet national and local health and safety requirements at any time.~~

7.3 Quality management system requirements

A quality management (QM) system that as a minimum meets the requirements in the ISO 9000 series standard shall be implemented by the manufacturer.

It is the obligation of the manufacturer to fulfill the manufacturing requirements laid down in this document and to include them in the QM system.

As a minimum, the QM system shall meet the requirements of the QM model according to ISO 9001. The QM system shall be defined in detail in writing.

Other standards may be used as reference for the QM system. The requirement regarding detail levels and documentation shall be comparable to those requirements specified in ISO 9001.

~~A separate certification of the QM system by a certification body accredited according to ISO/IEC 17021 or equivalent is recommended but not mandatory.~~

~~If the manufacturer does not hold a certification of the QM system, the QM system shall be included in the manufacturing evaluation with reference to IEC certification scheme.~~

7.4 Manufacturing process requirements

7.4.1 General manufacturing requirements

In Subclauses 7.4.2 through 7.4.12, basic requirements for manufacturing processes typically used in blade manufacturing are given.

Any manufacturing process external to normal processes (such as maintenance, repairs) should be avoided during normal processes. If a process needs to be interrupted (i.e. weekend), actions should be taken such that there is no adverse effect in the final product due to the interruption.

Contamination from external factors that could affect a process (e.g., dust, paint, and spray in laminating/gluing area) should be taken into account.

Operation of dust-generating machinery, painting or spraying work is only permissible within the laminating workshop if the manufacturer can ensure that such activities will not negatively affect the laminating quality.

For the preparation and processing of materials, the instructions of the material manufacturer plus any other applicable regulations, such as those of the relevant safety authorities, shall be observed in addition to this document.

7.4.2 Gelcoat application to the mould

If surface finish is to be achieved by means of a gelcoat, the gelcoat shall be mixed and applied on the mold in accordance with the process specification, using a suitable process.

Curing level and/or allowable time range for application of the first layer of laminate to the gelcoat shall be specified.

As a minimum, the following CTQ shall be specified and recorded:

- thickness of the gel-coat (wet or dry).

7.4.3 Building up the laminate

7.4.3.1 General

The laminate shall be built up in accordance with the process specification.

For sandwich core materials, it shall be ensured that the conditions of the material during processing are defined and controlled. This may include, but is not limited to, degassing, tempering and controlling humidity.

Extension of layers (creating a joint when fiber length/roll is insufficient) may only take place if described in work instructions.

Pre-shaped components such as wood or foam kits, fiber stacks, etc. shall be specified and processed in a way ensuring repeatability.

Controls shall be in place such that prefabricated components incorporated into the laminate do not adversely affect the overall structure.

As a minimum, the following process parameters should be specified, controlled and/or monitored:

- gaps and steps in between adjacent core segments;
- position of layers, including overlap between layers;
- alignment of fibers.

7.4.3.2 Consolidation of the laminate

The layers shall be adequately consolidated and compressed so that subsequent process requirements are met.

7.4.3.3 Application and curing of resin

It shall be documented that the process can produce the specified design within the acceptance criteria, including dry areas or air content and within fiber volume or mass fraction percentage as defined in material requirements to meet design strength values.

The application process shall be suitable for the resin system used.

Resin and reaction agent shall be mixed homogeneously and without any intrusion of air. If mixing machines are used, a procedure to verify and control the correct mixing ratio for each manufacturing cycle shall be defined.

Hand layup processes (such as resin mixing, mechanical preparation (rolling) to release trapped air or other gasses in the laminate, and cure) shall be controlled such that the specified final laminate quality is ensured.

During production, the processing time for the mixed resin compound specified by the manufacturer shall not be exceeded. In the absence of such information, the pot time shall be established in a preliminary test and the processing time limits described in the manufacturing specification.

Controls shall be in place such that prefabricated components incorporated into the laminate do not adversely affect the overall structure.

If vacuum assisted consolidation is required, the allowable process temperature and vacuum level, both as function of time, shall be defined.

For resin infusion, the relevant processing parameters shall be specified, at least including resin application temperature and time, vacuum set-up, as well as level of applied differential pressure for infusion and cure.

Inspection methods shall be defined for laminate imperfections (e.g., void content, dry laminates, inclusions, high or low resin content).

As a minimum, the following process parameters should be specified, controlled and/or monitored:

- cure cycle, resin temperature and vacuum level during cure and/or infusion process;
- time from mixing resin to complete application.

7.4.4 Adhesive bonding process

7.4.4.1 Surface preparation

The surface treatment procedure before bonding shall be specified. The process for preparation of surfaces to be bonded shall be suitable for the substrates and adhesive material used.

Typical surface treatment procedures may include mechanical roughening (e.g., rough-grinding, grit or sand-blasting, removal of peel-ply) and chemical etching.

Surface preparation degradation (e.g., moisture and dust accumulation, time elapsed between surface treatment and bonding, and environmental conditions) shall be considered.

Acceptance criteria for surface condition before bonding shall be specified with respect to dust and surface contamination and meet the requirements for the specific adhesive used.

If required by the adhesive type, the surfaces of the materials to be bonded together shall be free of contaminants (e.g., moisture, release agents, wax, grease, oil, dust, rust, or solvents). When using solvents for cleaning purposes, compatibility with the material shall be ensured.

If FRP components are to be bonded, minimum and maximum curing level before bonding shall be specified.

7.4.4.2 Application of adhesive

The processes for mixing and application of the adhesive shall be suitable for the substrates and adhesive material used. Procedures to control and verify the correct mixing ratio shall be defined. Processes shall be controlled such that the specified final adhesive properties are achieved.

The nominal values and tolerances of adhesive-layer width and thicknesses, as well as the maximum size and extent of permissible variations (e.g., voids, fillet radii), shall be defined.

The adhesive shall be processed in accordance with the manufacturer’s instructions. The proportion of fillers may not exceed the permitted limit. The adhesive shall be mixed in such a way that a homogeneous mixture is achieved.

The time from mixing of the adhesive until end of application and final joining of the parts in the correct position shall be specified and recorded, taking into account environmental conditions.

7.4.4.3 Quality assurance

Compliance of the bond line geometry with design specifications shall be ensured. This may be achieved either through use of a controlled process with demonstrated stability or by inspection of each part. For example, mold dry closure test (joining the parts without permanent bonding in order to verify bond thickness or gaps), visual inspection, and/or NDT measurements may be used to show compliance with manufacturing requirements.

As a minimum, the following process parameters should be specified, controlled and/or monitored:

- bond width;
- bond thickness;
- cured adhesive hardness;
- mixed adhesive viscosity;
- void content;
- open time for surfaces prior to bonding;
- time from start of mixing adhesive to complete joining of parts.

7.4.5 Curing

Resin and adhesive systems shall be cured such that the required final properties as defined in design specifications are achieved. This may include curing in accordance with the resin or adhesive manufacturer’s instructions or the results of suitable previous investigations. This requirement includes post-curing operations.

Cure time-temperature profiles shall be controlled and recorded such that design properties of the adhesives and resins are achieved. Tolerances on these profiles shall be defined.

Cure of resins and adhesives shall not adversely affect blade components. For example, maximum temperatures occurring during cure should not exceed the maximum allowable temperature for PVC foam or tooling materials.

A sufficient degree of cure shall be achieved before proceeding with operations (e.g., demolding or blade/prefabricated component movement) that would result in damage to structures.

The degree of cure shall be verified and documented.

As a minimum, the following process parameters should be specified, controlled and/or monitored:

- degree of cure, if applicable.

7.4.6 Demoulding

The demolding process of the blade or blade components shall be defined and described.

7.4.7 Trimming, cutting, and grinding

Trimming, cutting, and grinding processes include all operations that will mechanically remove material. This includes, but is not limited to:

- drilling holes in the structure;
- milling the root face;
- trimming and cutting excess material resulting from laminating processes;

- sanding and grinding operations.

Trimming, cutting, and grinding processes shall be defined such that the blade structure is not degraded by the processes and that critical dimensions meet design criteria.

7.4.8 Surface finish

Surface finish may include painting (including primer/paint systems), gelcoat, and leading edge protection.

For the application of surface finishes (except gelcoat), the application process and surface conditions shall be specified.

The primer or paint mixing process and the application processes shall be controlled in accordance with the process specification and shall be suitable for the materials used. Processing parameters and tolerances shall be defined, controlled, and documented to meet design requirements, including but not limited to mixing ratio.

The finish process shall provide the required adhesion between the finish and structural laminate. Curing level and/or time allowable range for application of the finish to the laminate surface shall be specified.

Thickness of finishes shall be specified with tolerances either before or after curing. Measurements of thickness shall be recorded evenly over the blade surface.

If applicable, leading edge protection systems (LEP) and their application processes shall be specified. Processing parameters and tolerances for LEP shall be defined, controlled, and documented to ensure the final LEP meets specified requirements.

As a minimum, the following process parameters should be specified, controlled and/or monitored:

- surface finish: gloss, color, roughness;
- level of cure;
- surface coating thickness.

7.4.9 Sealing

Unless demonstrated to be not necessary, laminate surfaces without surface protection shall be sealed using suitable agents. In particular, the cut edges of cut-outs and glued joints shall be carefully protected against environmental effects (e.g., moisture or UV radiation).

The sealing materials used shall not impair the properties of the laminate. They shall also suit the intended purpose of the component.

7.4.10 Additional component assembly processes

If in workshop assembly or installation of sub components or additional features takes place, this shall be described in work instructions including geometric positions and process or torque values with tolerances. This includes, but is not limited to:

- root connection parts;
- blade bearings;
- blade root bolts;
- lightning protection system components;
- drainage systems;

- mechanical tip brake systems;
- joints in segmented blades;
- aerodynamic devices (e.g., vortex generators).

7.4.11 Mass and balance

The balancing process including the use of equipment, handling and installing balancing material shall be specified in work instructions.

Features or equipment which is not part of or added after the balancing process, shall be quantified and included in the blade documentation.

As a minimum, the following CTQ shall be specified and recorded for each blade after balancing:

- blade total mass;
- blade center of gravity position or blade mass moment (including reference position);
- the balance weight added (for each balancing location if applicable).

7.4.12 Manufacturing and assembly processes outside controlled environment

Any manufacturing or assembly process taking place outside controlled environment shall be considered for sensitivity to external climatic conditions. This applies to work performed outdoor etc.

If these operations outside controlled environment are considered as part of the standard manufacturing process (e.g., scratch repair after blade transportation, cleaning surface before blade erection) they should be documented and demonstrate that they will not affect any of the design requirements or performance of the blade.

Materials should be specified to be compatible with the new environmental condition as well as compatibility with the standard materials used in the workshop.

For laminating or bonding processes, the environmental limitations shall be defined for minimum the following parameters:

- temperature;
- humidity;
- wind speed;
- surface preparation and contamination.

Condensation on material surfaces due to temperature and dew point shall be considered.

7.5 Manufacture of natural fiber-reinforced rotor blades

The mechanical properties for natural fibers (including wood, bamboo and other naturally-grown fibers) may be more sensitive to the processing. Processing parameters and limitations shall take this into account.

For natural fiber materials, the requirements of the species, producing area and age of the raw materials should be clearly defined. If relevant to the material, pre-sorting shall be used to ensure that the material meets the required quality standard. Moisture contents shall be defined and controlled to ensure that laminated materials meet the documented requirements prior to and during processing.

Qualification of materials for the manufacture shall take into account the additional variability of mechanical properties for strength, stiffness and density of natural fibers.

For characteristics regarding natural fibers not covered in this document, alternative industrially accepted standards can be adopted.

7.6 Other manufacturing processes

For other manufacturing processes not covered under Subclauses 7.4 and 7.5 (“Manufacture of fiber reinforced blades” or “Manufacture of natural fiber reinforced blades”), it shall be ensured that similar documentation and quality level as described for fiber reinforced material processes or natural fiber processes is documented.

7.7 Quality control process

7.7.1 Manufacturing quality plan

A manufacturing quality plan shall be defined with list of inspections and documents for each manufacturing step.

7.7.2 Incoming inspection

The manufacturer shall establish incoming inspection procedures, including applicable methods, to ensure that materials and components that are used in the manufacturing process comply with the properties and tolerances, defined in the design or material specifications.

Incoming materials inspection shall include, but is not limited to:

- structural fiber reinforcements;
- structural resins;
- structural adhesives;
- prepregs;
- gelcoat and paint;
- structural core materials;
- structural bolts and fasteners, including root inserts.

Methods for incoming materials inspection could include:

- incoming inspection certificates;
- verification by suppliers documented quality control procedures;
- internal checks for any damage;
- specified internal testing with defined sampling rate or frequency.

Acceptance criteria for these methods shall be defined in the documentation.

Incoming inspection certificates may be based on ISO 10474-2.2 (EN 10204-2.2) and ISO 10474-3.1 (EN 10204-3.1) in connection with ISO 10474 (EN 10204), or equivalent alternatives.

7.7.3 Manufacturing and quality control records

Details of the production process shall be laid down by specifications and work instructions, which also contain documents for the recording of selected production process parameters, e.g., CTQ values, testing of the components.

The tasks and responsibility of the production and quality control departments shall be defined clearly, including competences for signing off process and quality documents.

At defined stages in the process, completion of the step is confirmed and checked by competent persons as prescribed in the quality plan.

The following data shall be recorded for each blade produced and stored in a secure location for the design life of the blade:

- blade serial number or similar unique identification;
- all critical to quality (CTQ) process and design items as measured or recorded during in-process checks, approvals and inspection lists, and the corresponding limits;
- record of non-conformance reports (NRCs) and disposition/repair;
- batch numbers for materials with required traceability;
- identity (serial number or equivalent) of blade tooling used which affect CTQs.

Traceability of raw material (i.e. supplier, batch and lot numbers) used in the component shall be ensured for minimum the following items:

- structural fiber reinforcements;
- structural resins;
- structural adhesives;
- prepregs;
- gelcoat and paint;
- structural core materials;
- structural bolts and fasteners.

For other manufacturing processes using materials not covered by the above descriptions, it shall be ensured that similar documentation and quality records are documented.

7.7.4 Non-conformity process

7.7.4.1 Non-conformity identification and recording

A system to record and evaluate any non-conformity observed during manufacture shall be established (e.g., as part of a QM system according to ISO 9001).

It shall be ensured that non-conformities in manufacturing (e.g., exceedance of tolerances or acceptance criteria) are detected and documented.

7.7.4.2 Non-conformity evaluation and correction

A procedure for evaluation of corrective actions shall be established. Non-conformity shall be classified by severity and need for corrective action.

The severity shall be evaluated in compliance with the structural requirements of Clause 6.

Corrective action including structural repairs shall be categorized depending on structural severity, this should include the designer.

If corrective actions include acceptance or standard repair of non-conformities, this shall be taken into account in the design documentation.

7.7.5 In manufacture corrective action processes

For in-manufacture corrective actions, it shall be ensured that the resulting structure and geometry complies with the requirements of Clause 6.

For corrective actions including structural repairs, this compliance shall be demonstrated by the following means:

- full description/specification of the repair (preparation, materials, lay-up, processes etc.);
- design analysis according to the requirements of 6.6. This analysis shall include an explicit specification of the partial safety factors applied for the repaired structure. It is permissible to use partial safety factors different from those applied in the analysis of the unrepaired structure, provided that the conditions for the application of these factors as per 6.6.5 are fulfilled;
- full documentation of the repair performed (manufacturing protocol).

Structural repairs include but are not limited to:

- cutting, grinding and/or replacement of any continuous fibers;
- removal and/or replacement of any structural adhesive;
- removal and/or replacement of sandwich core material.

Non-structural repairs may include:

- paint or gelcoat repairs;
- minor filling of surface to meet geometry requirements;
- replacement of lightning protection parts.

7.7.6 Final manufacturing inspection and conformity review

A final inspection shall be carried out by the manufacturer.

The inspection procedure shall be specified and shall include, but is not limited to, the items below:

- check of the geometry including accuracy of profile data and trailing edge thickness;
- determination of the mass and the center of gravity;
- check of the balance quality for each set of blades;
- surface quality and appearance;
- drainage system (if applicable);
- functional checks of installed systems (to include – but not limited to)
  - brake system,
  - flaps or moving devices,
  - sensors and monitoring system,
  - lightning protection system;
- work progress sheets and check sheets which accompany the rotor blade through the production process;
- Completeness check of the data and entries in control sheets and inspection lists. Verification of data (CTQ) compliance with acceptance criteria.

Data and conclusions from final inspection shall be recorded and stored with blade manufacturing documentation.

7.7.7 Documentation

7.7.7.1 Identification marking of blades

Each rotor blade shall be permanently marked with a unique identity reference.

The unique identity can be by serial number and shall allow identification of production location and blade manufacturing documentation.

Furthermore, a permanent identification (e.g., a plate from non-corrosive material) shall be attached in an easily accessible position with at least the following information:

- manufacturer;
- type designation;
- serial number.

A reference for pitch setting angle shall be marked on the blade root, unless by the design this is defined by other means.

7.7.7.2 Blade documentation

The final inspection/check shall be documented.

The documentation shall contain minimum the following data for each rotor blade:

- manufacturer;
- rotor blade type designation (e.g., model/name);
- serial number and date of manufacture;
- mass and centre of gravity;
- mass moment (including geometric reference);
- type of aerodynamic brake, if applicable.

7.8 Requirements for manufacturing evaluation

~~For compliance with certification requirements when performing manufacturing evaluation with reference to IEC certification scheme, a specific requirement for rotor blade manufacturing evaluation applies.~~

The manufacturing evaluation shall include spot checks of the manufacturing processes critical to the material structural properties, including:

- layup of main structural fibers, core materials and/or components;
- resin application processes (if applicable);
- main bonding processes (if applicable) including surface preparation, positioning of components and glue application.

Special attention to quality procedures related to critical processes shall be made, including:

- cure processes.

As a minimum, the following documents shall be reviewed for compliance with the design and be available for the performance of the manufacturing evaluation audit.

- material qualification;
- work instructions and drawings, including process specifications with tolerances;
- quality control sheets, including acceptance criteria/tolerances for CTQ’s.

Requirements for the quality management system in relation to manufacturing evaluation as per 7.3 shall be met.

8 Blade Installation, operation and maintenance

8.1 General

Clause 8 defines requirements for information and requirements to be provided for safe handling, operation and maintenance of the blade.

The operational limits and ranges for the blade shall be defined.

Requirements needed for fulfilling conditions or assumptions in the blade design shall be specified and made available in the form of information material (e.g., manuals or similar) for persons handling, operating and/or performing maintenance of such blade, for the complete design lifetime.

The designer shall consider the need for any personal protection equipment, relevant for specified maintenance work. ~~This shall not replace any legal or national requirements.~~

~~For compliance with wind turbine type certification requirements other relevant standards may apply. This includes conformity with IEC 61400-1.~~

8.2 Transportation, handling and installation

Manuals shall include, but is not be limited to, instructions for lifting and handling, transportation and storage procedures.

Guidelines shall be provided which define all the work related to blade handling, including but not limited to lifting, storing, transporting and mounting.

If lifting and handling is limited by design to specific areas on the blade, the dimensions and position of such areas that are specified for use in lifting and handling the blade shall be included in the manual.

Location and reference (e.g., on the blade by a sticker, sketch or an attached instruction) shall be provided for:

- the centre-of-gravity (CG);
- dimensions and position of areas that are specified for use in lifting, handling and storage.

Allowable handling procedures shall define:

- the orientation of the blade during lifting and handling (e.g., flatwise or edgewise);
- which combinations of lifting locations can be used together;
- how blades shall be rotated;
- how to achieve protection of the whole blade, but in particular the leading and trailing edges;
- how to support and secure blades during storage and any applicable time limitations for storage.

Allowable maximum accelerations and loads during transportation shall be defined for the blade.

The dimensions and position on the blade of areas that allow for support during transportation and storage of the blade shall be clearly marked.

If transportation fixtures are mounted on the blade root using blade installation connection, the minimum number of bolts and the tensioning procedure shall be specified.

8.3 Maintenance

8.3.1 General

Inspection and maintenance requirements for lightning protection systems shall be described according to the requirements in IEC 61400-24.

If the blade design requires any further routine maintenance or inspections, this shall be specified.

If procedures for blade cleaning are prescribed, acceptable means of cleaning process including any limitation in the use of chemicals, shall be stated.

A blade maintenance manual may describe defects that are acceptable for safe operation. If such defects are described and may cause structural degradation, then these shall be considered in the design and/or testing.

8.3.2 Scheduled inspections

If scheduled inspections are required, the following shall be specified:

- the type of inspection, along with its intervals and timing;
- the blade areas to be inspected;
- applicable acceptance criteria.

Typical inspection locations may include but are not limited to:

- trailing edge;
- leading edge;
- spar cap;
- root connections/root seals;
- blade tip/drain holes;
- lightning protection systems and recorders;
- blade panel surfaces;
- internal areas, e.g., shear webs;
- blade mechanical systems, e.g., tip brakes.

CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

Wind energy generation systems - Part 5: Wind turbine blades

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.

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This consolidated version of the official IEC Standard and its amendment has been prepared for user convenience.

IEC 61400-5 edition 1.1 contains the first edition (2020-06) [documents 88/759/FDIS and 88/767/RVD] and its amendment 1 (2025-08) [documents 88/1086/FDIS and 88/1107/RVD].

This Final version does not show where the technical content is modified by amendment 1. A separate Redline version with all changes highlighted is available in this publication.

International Standard IEC 61400-5 has been prepared by IEC technical committee 88: Wind energy generation systems.

The text of this International Standard is based on the following documents:

FDIS	Report on voting
88/759/FDIS	88/767/RVD

Full information on the voting for the approval of this International Standard can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

Future standards in this series will carry the new general title as cited above. Titles of existing standards in this series will be updated at the time of the next edition.

A list of all parts of the IEC 61400 series, under the general title *Wind energy generation systems*, can be found on the IEC website.

The committee has decided that the contents of this document and its amendment will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn, or
- revised.

INTRODUCTION

The blades of a wind turbine rotor are generally regarded as one of the most critical components of the wind turbine system. In this International Standard, a minimum set of requirements for the design and manufacturing of wind turbine blades are defined.

An approach to a structural design process for the blade is set forth in the general areas of blade characteristics, aerodynamic design, material requirements and structural design. Furthermore, in order to efficiently facilitate the transfer of a blade design to the production environment, this document includes demands for designing for manufacturing.

The requirements for structural design of the wind turbine blade have been developed in a manner to reward innovation, validation, quality and testing. Specifically, the designer will be able claim lower partial safety factors based on, among other items, the diligence of the validation of models and the correlation to testing results.

To ensure a production environment that can facilitate the manufacturing of a blade in accordance with the design, the manufacturing requirements included in this document provide a minimum basis for a quality management system and workshop requirements. In addition, requirements for blade handling, operation and maintenance are described in the close of this document.

WIND ENERGY GENERATION SYSTEMS –

Part 5: Wind turbine blades

1 Scope

This part of IEC 61400 specifies requirements to ensure the engineering integrity of wind turbine blades as well as an appropriate level of operational safety throughout the design lifetime. It includes requirements for:

- aerodynamic and structural design,
- material selection, evaluation and testing,
- manufacture (including associated quality management),
- transportation, installation, operation and maintenance of the blades.

The purpose of this document is to provide a technical reference for designers, manufacturers, purchasers, operators, third party organizations and material suppliers.

With respect to certification, this document provides the detailed basis for fulfilling the current requirements of the IECRE system, as well as other IEC standards relevant to wind turbine blades. When used for certification, the applicability of each portion of this document should be determined based on the extent of certification, and associated certification modules per the IECRE system.

The rotor blade is defined as all components integrated in the blade design, excluding removable bolts in the blade root connection and support structures for installation.

This document is intended to be applied to rotor blades for all wind turbines. For rotor blades used on small wind turbines according to IEC 61400-2, the requirements in that document are applicable.

At the time this document was written, most blades were produced for horizontal axis wind turbines. The blades were mostly made of fiber reinforced plastics. However, most principles given in this document would be applicable to any rotor blade configuration, size and material.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60050-415, *International Electrotechnical Vocabulary (IEV) – Part 415: Wind turbine generator systems*

IEC 61400-1, *Wind energy generation systems – Part 1: Design requirements*

IEC 61400-2, *Wind turbines – Part 2: Small wind turbines*

IEC 61400-3-1, *Wind energy generation systems – Part 3-1: Design requirements for fixed offshore wind turbines*

IEC 61400-3-2, *Wind energy generation systems – Part 3-2: Design requirements for floating offshore wind turbines*

IEC 61400-23*, Wind turbines – Part 23: Full-scale structural testing of rotor blades*

IEC 61400-24, *Wind energy generation systems – Part 24: Lightning protection*

ISO 10474, *Steel and steel products – Inspection documents*

ISO 2394, *General principles on reliability for structures*

ISO 9000, *Quality management systems – Fundamentals and vocabulary*

ISO 9001, *Quality management systems – Requirements*

EN 10204, *Metallic products – Types of inspection documents*

ISO 16269-6, *Statistical interpretation of data – Part 6: Determination of statistical tolerance intervals*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60050-415 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
blade root
that part of the rotor blade that is connected to the hub/pitch-bearing of the rotor

3.2
blade subsystem
integrated set of items that accomplish a defined objective or function within the blade (e.g., lightning protection subsystem, aerodynamic braking subsystem, monitoring subsystem, aerodynamic control subsystem, etc.)

3.3
buckling
instability characterized by a non-linear increase in out of plane deflection with a change in local compressive load

3.4
characteristic value
value having a prescribed probability of not being attained (i.e. an exceedance probability of less than or equal to a prescribed amount)

Note 1 to entry: See 61400-1.

3.5
chord
length of a reference straight line that joins the leading and trailing edges of a blade aerofoil cross-section at a given spanwise location

3.6
creep
time-dependant increase in strain under a sustained load

3.7
design limits
maximum or minimum values used in a design

3.8
design loads
loads the blade is designed to withstand, including appropriate partial safety factors

3.9
design properties
material and geometric properties (including design limits)

3.10
edgewise
direction that is parallel to the local chord

3.11
environmental conditions
characteristics of the environment (wind, altitude, temperature, humidity, etc.) which may affect the wind turbine blade behaviour

3.12
flapwise
direction that is perpendicular to the surface swept by the undeformed rotor blade axis

3.13
flatwise
direction that is perpendicular to the local chord, and spanwise blade axis

3.14
inboard
towards the blade root

3.15
lead-lag
direction that is parallel to the plane of the swept surface and perpendicular to the longitudinal axis of the undeformed rotor blade

3.16
limit state
state of a structure and the loads acting upon it, beyond which the structure no longer satisfies the design requirement

3.17
load envelope
collection of maximum design loads in all directions and spanwise positions

3.18
natural frequency
eigen frequency
frequency at which a structure will vibrate when perturbed and allowed to vibrate freely

3.19
partial safety factors
factors that are applied to loads and material strengths to account for uncertainties in the representative (characteristic) values

3.20
prebend
blade curvature in the flapwise plane in the unloaded condition

3.21
spanwise
direction parallel to the longitudinal axis of a rotor blade

3.22
stiffness
ratio of change of force to the corresponding change in displacement of an elastic body

3.23
strain
ratio of the elongation (or shear displacement) of a material subjected to stress to the original length of the material

3.24
sweep
blade curvature in the lead-lag plane in the unloaded condition

3.25
twist
spanwise variation in angle of the chord lines of blade cross-sections

3.26
critical to quality
CTQ
process or design value that is measurable and specifies critical acceptance criteria

4 Notation

4.1 Symbols

F	load
F_d	design value for the load
F_k	characteristic value for the load
R	resistance of material or structure against the corresponding limit state
R_k	characteristic material resistance
PSF	Partial Safety Factor
S()	function for structural response to the load
T_g	glass transition temperature
$p_{\perp\parallel}$ (−)	negative Puck inclination parameter
$p_{\perp\parallel}$ (+)	positive Puck inclination parameter

4.2 Greek symbols

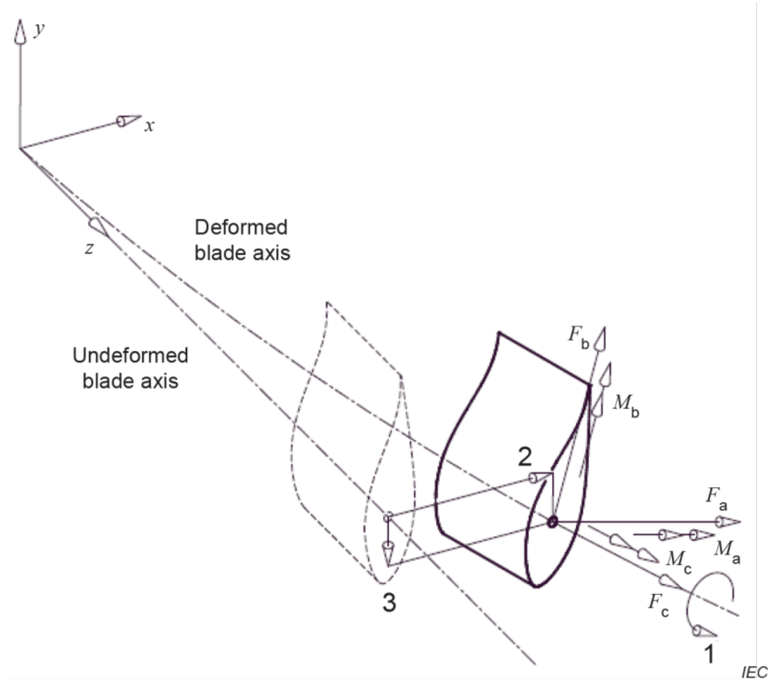
γ	Partial safety factor

4.3 Subscripts

m	materials
m0	materials as a “base” material factor (to be included in all analyses)
m1	materials for environmental degradation (non-reversible effects)
m2	materials for temperature effects (reversible effects)
m3	materials for manufacturing effects
m4	materials for calculation accuracy and validation of method
m5	materials for load characterization
n	consequence of failure
f	factor for loads

4.4 Coordinate systems

Coordinate systems for loads and design reference are shown in Figure 1 and Figure 2.

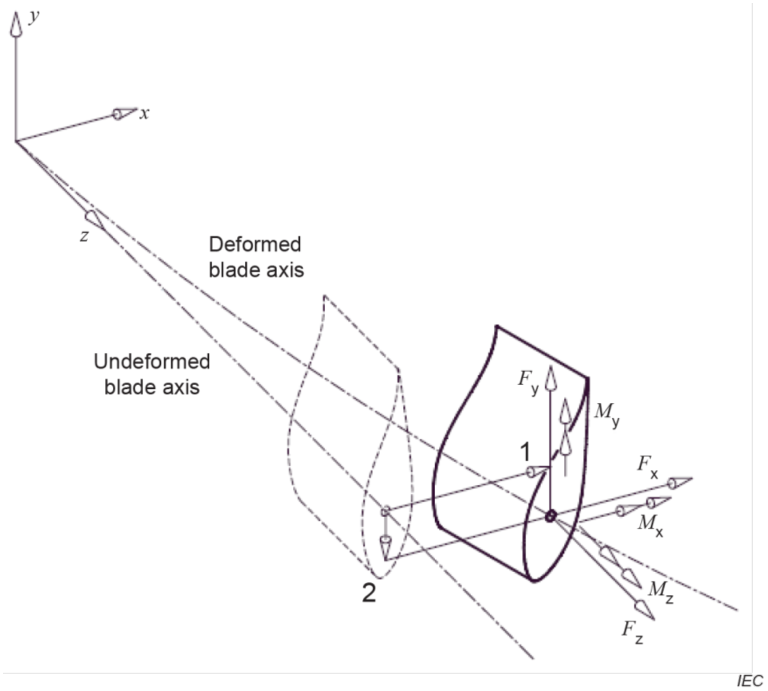


Loads are along and perpendicular to the local blade chord directions.

Key

M_a	edgewise bending moment
M_b	flatwise bending moment
M_c	torsion moment
F_a	flatwise shear force
F_b	edgewise shear force
F_c	axial force
1	torsion angle
2	flapwise translation
3	lead-lag translation

Figure 1 – Chordwise (flatwise, edgewise) coordinate system



Loads are along the rotor plane reference directions.

Key

M_x	lead-lag bending moment
M_y	flapwise bending moment
M_z	torsion moment
F_x	flapwise shear force
F_y	lead-lag shear force
F_z	spanwise force
1	flapwise translation
2	lead-lag translation

Figure 2 – Rotor (flapwise, lead-lag) coordinate system

5 Design environmental conditions

Wind turbine blades are subjected to environmental conditions that may affect their loading, durability and operation. To ensure the appropriate level of safety and reliability, the design environmental conditions shall be taken into account and explicitly stated in the design documentation. This shall include but is not limited to the environmental conditions specified in IEC 61400-1, IEC 61400-3-1 or IEC 61400-3-2, and IEC 61400-24 (for lightning).

The environmental conditions are divided into normal and extreme categories. The normal environmental conditions generally concern recurrent structural loading conditions, while the extreme environmental conditions represent infrequent external design conditions. The design load cases defined in IEC 61400-1, IEC 61400-3-1 or IEC 61400-3-2 include combinations of these environmental conditions with wind turbine operational modes and other design situations.

When additional environmental conditions not listed in the above references are specified by the designer, the parameters and their values shall be stated in the design documentation.

It shall be taken into account that these environmental conditions may vary for different phases of the product lifecycle (manufacturing, transport/storage, installation, operation or dismantling).

6 Design

6.1 Structural design process

6.1.1 General requirements

The structural design process shall ensure that the required operation safety levels are met for the entire design lifetime and loading of the blade.

The design shall be sufficiently described and specified to ensure that assumptions made during the design process can be met and complied with during the manufacturing process.

The allowable manufacturing tolerances and acceptance criteria shall be defined by the designer and specified in the design documentation.

Any of the requirements of this document may be altered if it can be suitably demonstrated that the safety of the wind turbine system is not compromised.

6.1.2 Building block approach for composite structural design

The traditional detailed design (analytic and numerical calculation together with validated material data and full blade testing) of FRP structures can be enhanced by a building-block approach, starting with coupon-level tests, analysis and testing of more complicated structures; and culminating in a full blade test. This relationship is shown in Figure 3, where increasingly more complex tests are developed to evaluate more complicated loading conditions and failure modes.

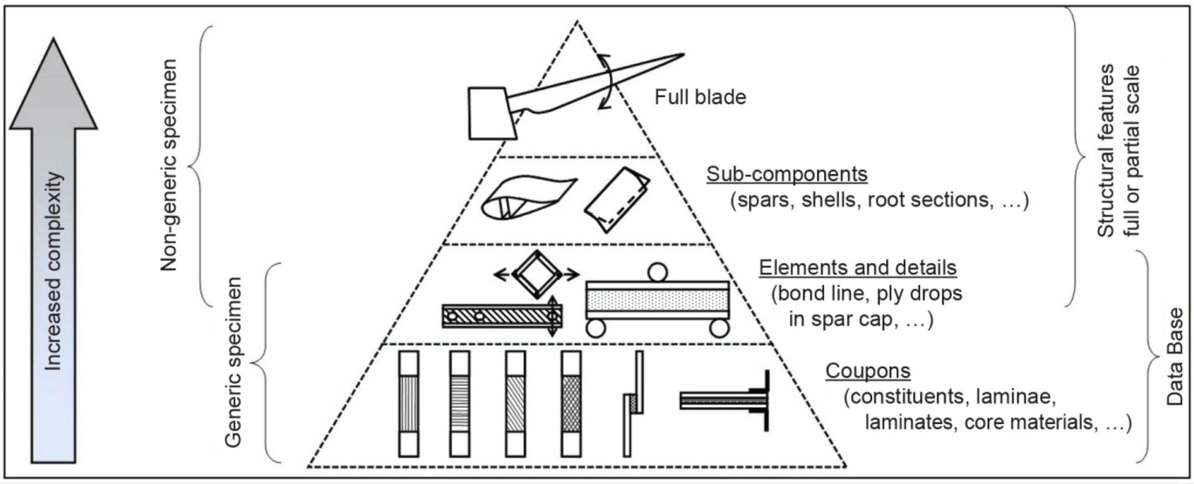


Figure 3 – The building block approach

The approach can be summarized as follows:

Coupons: A number of tests are conducted at the coupon level, where confidence in repeatable physical properties is developed. Procurement specifications are developed for the individual constituents, and allowable design variables developed for lamina/laminate combinations.

Elements and details: Critical areas from the design analysis identify elements for further testing and analysis at the design conditions with representative specimens. This may include such tests as the spar cap to web bond line or ply drops in the spar cap laminate.

Sub-components: Parts and sections representative of the blade design are tested to evaluate specific loading conditions and failure modes. Examples include spars, shells and root sections. The test components may be full or partial scale where demonstrated to be representative.

Full blade: A full blade or significant part of a blade, representative of the blade design is tested to evaluate specific loading conditions and failure modes. The blade may be full or partial scale where demonstrated to be representative.

The number of tests required for each level should be tailored for each design activity, with the blade designer responsible for the development of a reasonable number of tests at each stage.

Tests on the element and detail as well as sub-component level will increase the confidence in the structural design.

For design values (strength, stiffness, etc.) developed from test at any building block level (material sample, sub-component, etc.), the validity of such design values shall be described and limited by acceptance criteria[1] and tolerances to be met in the final design.

6.1.3 General blade design process

A typical process, provided for informative guidance only, for the design and analytical evaluation of a blade is illustrated in Figure 4. In addition to the steps shown, the design process can include the development of critical inputs, such as establishing aerodynamic characteristics of airfoils, and characterization of materials properties.

The iteration loops shown are only indicative and may not represent all specific design processes. For example, if an aerodynamic design evaluation is not found satisfactory, the designer may re-consider the airfoils used (as shown in the figure), or iterate at another step of the aerodynamic design process.

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[1] Note on acceptance criteria (example only): for a laminate coupon sample tested for fatigue strength, the acceptance criteria may amongst other include definition of raw materials (reference to material specifications), fiber volume fraction, fiber alignment angles, manufacturing and curing process, etc.

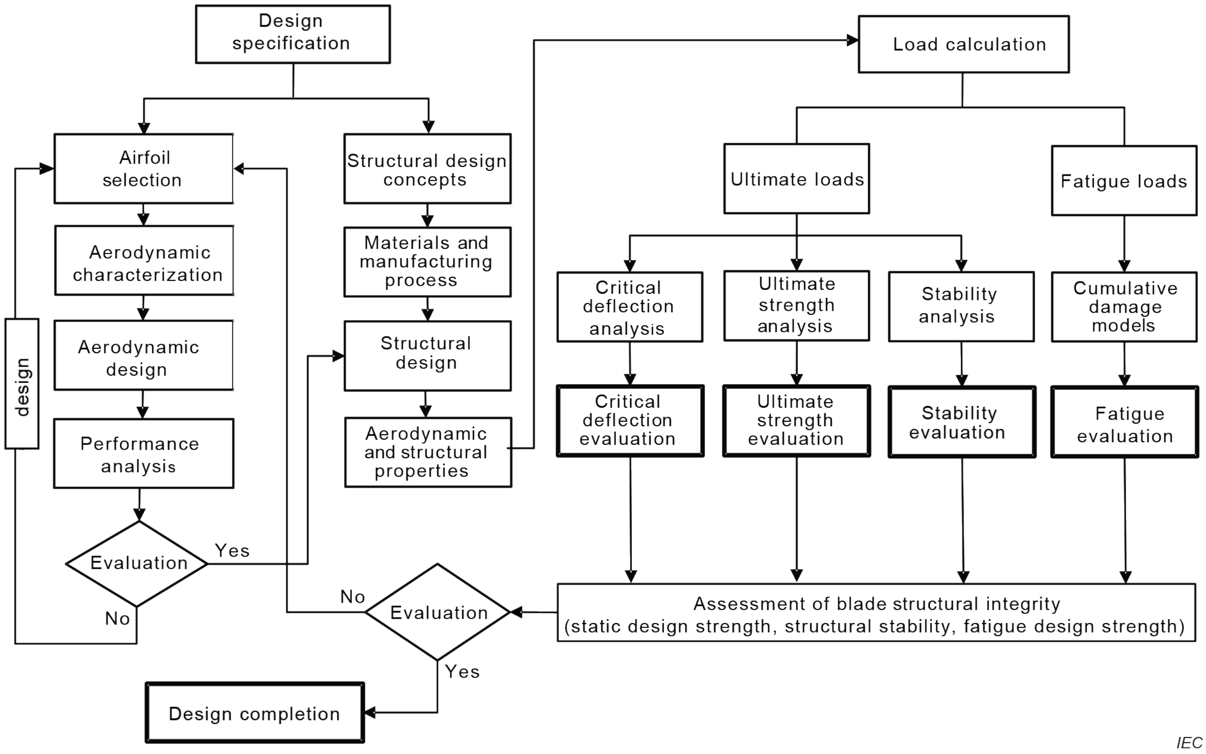

Figure 4 – Typical process for design and analytical evaluation of blade

As noted in Figure 4, the blade structural integrity is to be evaluated for avoidance of specific failure modes. Evaluations can be based on analysis or tests or a combination of analysis and tests (see building block approach, Subclause 6.1.2). This is in conformity with IEC standards (e.g., IEC 61400-1, IEC 61400-3-1, IEC 61400-3-2) which require the use of the limit states design approach.

In the most general sense, the limit states design approach involves the characterization of structural responses resulting from loads (e.g., stress, strain or deflection) and resistance to those responses (e.g., strength, stiffness). Partial safety factors (PSFs), γ, are applied to account for uncertainties in the calculated response and resistances so that the probability of exceeding limit states is acceptably low.

Characteristic loads are those predicted to occur with a specified probability. The design values for loads are determined by multiplying by loads partial safety factors, γ_f.

Resistance is normally a function of material properties. Characteristic resistance is calculated from test results, where the default is 95 % exceedance with 95 % confidence level according to ISO 16269-6. It should be stated if statistical tolerance limit factors for known or unknown population standard deviation are used.

The resistance of the structural materials as embodied in the full blade structure may be different than as measured at the coupon level. In some cases, this may be due to predictable effects of scale, geometry, and load-introduction. Other effects could include variations in material properties (e.g., composition, mechanical properties, orientation). The material partial safety factor, γ_m, is intended to cover combined uncertainties in the relationship between coupon-based resistance and the resistance in the as-built blade. Subclause 6.6.4 gives detailed definition of how γ_m is defined.

According to IEC 61400-1, partial safety factors for consequences of failure, γ_n, shall also be included. In principle, γ_n can be applied either as an increase in the response, or a decrease in resistance as shown in Figure 5.

In all verifications, the design value of response shall not exceed the design value of resistance. Figure 5 shows these two values being separated by a safety margin. Verification requires safety margin values greater than or equal to zero.

For some limit states, the relationship between material properties and resistance against failure in the limit state is not linear (e.g., in a fracture mechanics and buckling analyses). For such cases, the PSFs shall be applied in such way that they have a linear relation with the load carrying capability as in the following equation:

$$S(\gamma_\mathrm{f} \times F_\mathrm{k}) \leq \frac{R_\mathrm{k}}{\gamma_\mathrm{m}\gamma_\mathrm{n}}$$

where S is a function for the structural response to the load and R_k is the characteristic material resistance.

This general formulation is shown in Figure 5, where partial safety factors are introduced in a relationship between the structural response due to loads and the resistance for the corresponding limit state.

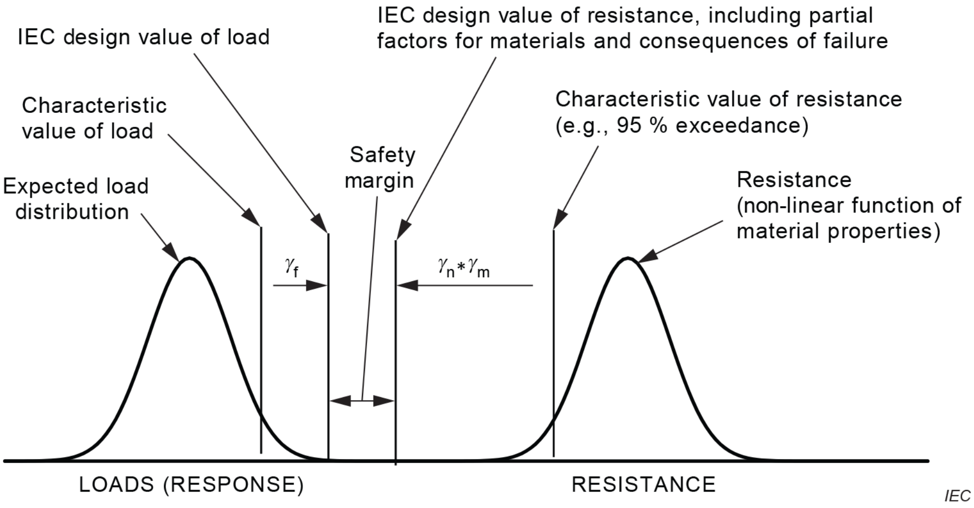

Figure 5 – Application of limit states design approach for blade verification

Material resistance may be expressed either in stress or strain.

As discussed in 6.6, γ_m is derived by consideration of numerous contributions to the overall resistance uncertainty. At the time this document was written, typical industry practice was consistent with the illustration in Figure 3, with material resistance developed by coupon-level testing to determine material properties which are then translated to blade-level using a value of γ_m that covers a wide number of uncertainties. Numerous strategies are possible by which uncertainties in the transfer of material-level properties to the resistance in the as-built blade can be reduced.

For example, by using the building block approach, a combination of failure modes and limit states are taken into account with a lower uncertainty with increased size and complexity of the building block tested. Obtained strength and stability values will define failure modes for material samples and sub-components, and shall be compared with analytical methods for validation.

6.1.4 Design loads

6.1.4.1 Design envelope

The design loads for a blade can be specified for a single wind turbine design, or it can be given as a wider load envelope intended to cover a range of wind turbine designs.

The defined loads/load envelope may be based on the design load cases specified in IEC 61400-1, including non-operational situations (e.g., transportation, handling, installation, maintenance, loading of attachment points). For offshore turbines, the requirements in IEC 61400-3-1 and IEC 61400-3-2 should be considered.

6.1.4.2 Load interaction

The structural characteristic of the blade interacts with its aerodynamic loading and the turbine controller. For a safe operation of the blade in rotational and stand still conditions, it shall be assured that any instability (e.g., flutter) or resonance as a result of the interaction of aerodynamic loading, blade structural design, turbine control (rotational speed, pitch angle, etc.) and support structure has been considered in the load calculation.

The structural design of the blade shall reflect the defined operational, transportation and handling load envelope, and the structural verification shall prove that the blade can withstand the specified ultimate and fatigue design loads.

6.1.4.3 Load envelopes

Due to the asymmetry of rotor blade structures, the assumed loads in the analysis may not reflect the most critical loading direction for any given failure mode. There are two approaches to account for the critical loading direction.

- Basic approach: Usage of four matched sets of loads (moments and forces) corresponding to the extremes of flatwise and edgewise loads. The angle of the resulting load vector shall be considered. For certain verifications, this may be insufficient to cover the most critical load directions for combined loading. This shall be considered in the design.
- Advanced approach: Consideration of all potentially critical loading directions within a cross section. Without further analysis of load criticality, a set of loads distributed evenly in at least twelve directions is considered sufficient for this approach.

The components of an extreme load envelope are not generally contemporaneous (happening at the same time) and therefore this loads envelope represents a conservative condition. This conservatism may be reduced by evaluating the structure for each of the contemporaneous loads that comprise the extreme load.

In general, it is sufficient to design for the resultant bending moments. However, this may not always be the most critical loading type for all failure modes. For example, the highest shear forces represent the most critical loads for the verification of bond strength. Torsional loading should also be considered.

To ensure that loads are calculated at a sufficient number of spanwise sections, loads shall be available at minimum 12 cross sections along the blade length (spanwise).

The spanwise distance between load definition sections shall not be larger than 2,0 × the smallest chord length for the given section, for the sections from root to 85 % of blade length.

Geometry or stiffness variations shall be considered during section selection.

6.2 Blade characteristics

6.2.1 Blade properties

Structural and aerodynamic properties of the blades are critical to the aero-elastic loading of the blade and turbine.

The characteristics of the blade shall be defined for use as input for loads calculation. These characteristics shall include mechanical and physical properties at discrete sections along the length of the blade, for the relevant degrees of freedom that are related to the relevant design states:

- distribution of aerodynamic profiles, chord, aerodynamic twist, and thickness;
- aerodynamic characteristics (i.e., lift, drag, and pitching moment coefficients as a function of angle of attack) associated with the aerodynamic profiles;
- elastic stiffness properties (e.g., flatwise and edgewise stiffness and if significant to the design, torsional and extensional stiffness) and their reference axes;
- distributions of mass and mass moments of inertia and the reference axis;
- elastic coupling (e.g., flatwise vs. edgewise, flatwise vs. torsion or similar, if significant to the design);
- structural damping.

Structural properties shall be defined for a minimum number of sections along the blade. These shall not be less than those specified for structural verification according to 6.6.3.1.

6.2.2 Functional design tolerances

Tolerances shall be defined for the following parameters:

- shape of the aerodynamic profiles, including but not limited to:
  - radius of the profile leading edge;
  - relative thickness of the profile;
  - local chord length;
- roughness of the profile surface;
- aerodynamic twist angle;
- blade length;
- geometric position of blade aerodynamic profiles relative to blade root reference;
- geometry and position of any static or moveable aerodynamic device (vortex generator, flaps, etc.);
- the nominal 0° pitch marking;
- blade mass;
- blade static moment (for each individual blade and relative to blades in a blade set);
- blade natural frequencies;
- angular and flatness tolerance for blade face flange.

Tolerance ranges for the above listed parameters shall be accounted for in the design evaluation of loads, performance and structural integrity, in case they are judged as not negligible for consideration of safe operation of the blade.

The actual values of the tolerances shall be specified and considered by the designer.

If the designer does not specify alternative values, the following values are generally acceptable without further technical justification.

• profile[2]	
– shape of the profile	±0,2 % × chord
– roughness of the profile surface[3]	$R_z \leq 15$ µm
– local chord length (for the inboard 80% of span)	±1,0 % × chord
• twist angle distribution	±0,2°
• blade length	±0,1 % × length
• setup of 0° marking	±0,2°
• blade mass	±3,0 %
• blade static moment	±4,5 %
• blade static moment, difference in one set	±0,2 %
• blade natural frequency	±5,0 %

6.3 Aerodynamic design

6.3.1 General

The assessment of the aerodynamics of the rotor blade will generate input data for load calculations and power performance calculation evaluation based on both experimental and computational results.

6.3.2 Aerodynamic characteristics

The aerodynamics of the blade shall be characterized. The full 360° range of angle of attack and all flow regimes should be considered.

One or a combination of any of the following approaches shall be used to evaluate the aerodynamic characteristics of the blade (where appropriate, the models and tools employed shall be validated):

- 3D simulation (computational fluid dynamics, boundary element method, vortex lattice method, etc.);
- 2D simulation of the aerodynamic characteristics of the profiles;
- justified assumptions regarding the aerodynamic profiles characteristics for the range of angle of attack with flow separation;
- wind tunnel tests for at least the range of angle of attack to obtain the aerodynamic characteristics in the area of maximum positive and negative lift coefficient.

The evaluation shall take into account realistic Reynolds and Mach numbers.

To ensure a realistic load and performance analysis, the effect of blade roughness during operation should be considered. The evaluation defined above shall be done for a sufficient number of aerodynamic profiles to characterize the aerodynamic behavior of the whole blade.

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[2] The influence of these tolerances depends on the profile specific characteristics and the location on the blade surface; the blade leading edge and outboard areas are most sensitive to shape deviations and roughness.

[3] This tolerance applies to gelcoat and painted surfaces; soiled blade surfaces due to operation are not covered by this tolerance and shall be considered by suitable design assumptions.

As a minimum one aerodynamic profile with a relative thickness between 75 % and 50 %, one profile with a relative thickness between 50 % and 30 %, and two profiles with a relative thickness below 30 % shall be assessed.

3D effects shall be taken into account.

Any additional aerodynamic devices (flaps, vortex generators, serrations, etc.), which are planned to be used on the blade, shall be evaluated.

6.3.3 Power performance characterisation (informative)

The power performance of the blade should be considered to evaluate its efficiency. To get a reliable characterization of the rotor power characteristic the following points should be taken into account:

- reliable aerodynamic blade model, assessed according to 6.3.2;
- appropriate turbulence of the wind field;
- appropriate vertical gradient of the wind field;
- appropriate air density and temperature of the wind field;
- appropriate simulation model of the turbine control unit (speed and [single and/or collective] pitch control);
- influence of airfoil surface roughness that is representative of expected surface conditions.

The deformation of the blade (e.g., twist and profile deformations) during operation should be taken into account for a reliable power characterization.

6.3.4 Airfoil noise (informative)

The noise generation of the blade should be considered. Appropriate analytical or computational approach should be used and special aerodynamic devices present on the blade should be taken into account.

6.4 Material requirements

6.4.1 General

For fiber reinforced composite materials, the strength and stiffness values are dependent on the properties of the raw materials and the manufacturing processes.

The following steps are essential to ensure that the materials meet the design requirements:

- The design values for strength and stiffness of materials used for structural composite members shall be specified.
- Materials require a qualification proving that they meet the specified values. The qualification shall be documented and a process shall describe necessary tests to be performed.
- For raw materials for composite material manufacture, the designer should define critical parameters or values to be verified and/or tested during incoming goods inspections.

6.4.2 Material properties for blade design

6.4.2.1 Characterization

Material properties used for blade design includes design values for combined materials (e.g., fiber composites), bond lines (e.g., including strength of adhesive and complete bond line assembly), sandwich design (e.g., including sandwich core materials and their interaction with face sheets).

The material properties and design values are what determine material compliance against specific blade functional requirements and as such constitutes the basis for material selection. Material requirements for blade design are properties of the resulting material, product, or subsystem.

The designer shall select appropriate test specimens using manufacturing processes representative for those used in the blade serial production. It is recommended to follow the building block approach described in 6.1.2.

Due to the nature of composite materials, some material properties are best determined with element and/or component level specimen configurations.

The characterization of material mechanical properties shall be established based on statistical evaluation, such as mean values, standard deviation, etc. If not stated differently, a survival probability of 95 % with 95 % confidence level shall be used. Results on smaller scale tests may be used to estimate the scatter of larger scale tests.

In cases where test methods are not available, the materials mechanical properties may be documented by validated calculation methods, e.g., synthesized classical laminate theory (CLT), or failure models provided that the accuracy of the models can be demonstrated through validation by testing. Any uncertainty resulting from this shall be represented in the corresponding PSF.

The use of design values from recognized guidelines is acceptable. The source reference shall be stated, however it should be noted that the values used are often conservative.

Specimen conditioning/ageing:

For nominal design properties, specimens are tested without condition and ageing. If required in connection with specific material partial safety factors γ_{m1} as in 6.6.5.2, additional tests shall be carried out on specimens that have been conditioned/aged in accordance with the specific choice of partial safety factors.

Test temperature:

For nominal design properties, specimens shall be tested at room temperature. If required in connection with specific material partial safety factor γ_{m2} as 6.6.5.2, additional tests shall be carried out at the required temperatures in accordance with the specific choice of partial safety factors.

Manufacturing process:

For nominal design properties, specimens are tested without consideration of the effects of blade manufacturing tolerances.

Elastic properties:

For applications outside the extreme temperature range for the standard wind turbine classes according to the IEC 61400-1, the changes in elastic properties of blade materials shall be taken into account.

6.4.2.2 Fiber reinforced laminates

FRP (fiber reinforced plastic) materials consist of a fibrous reinforcing component material, which provides the main strength and stiffness properties, combined with a polymeric matrix component (resin) providing support, stress transfer and protection to the fibers.

Each individual laminate type (unidirectional, biaxial, and multiaxial) should be tested separately. The scope of required testing may be reduced (using a higher γ_{m3} and/or γ_{m4}, see 6.6.4) when the same constituents are used in the different laminates (e.g., UD, BX and Multiaxial laminates made from the same fibers, with similar lamina thicknesses, and with the same resin matrix), or when the test specimens are built with material combinations and lay-ups representative for the blade design.

The following material properties shall be tested, and statistically derived characteristic values for strength properties shall be obtained.

Physical properties for each test panel:

- fiber volume fraction and void content;
- state of cure (e.g., T_g for epoxy);
- cured ply thickness.

Static tests:

- longitudinal [0°] tensile: strength, modulus, strain, Poisson′s ratio;
- transverse [90°] tensile: strength, modulus, strain;
- longitudinal [0°] compression: strength, modulus, strain;
- transverse [90°] compression: strength, modulus, strain;
- in-plane shear: strength, modulus;
- interlaminar shear: strength (e.g., short beam).

Fatigue tests:

- longitudinal [0°]: strength

A reasonable spread of number of cycles shall be demonstrated e.g., 4 consecutive decades, with 3 samples in each decade. One of the decades shall exceed 10^6 cycles. If tests are done at only one R ratio, this should be $R = -1$. For compliance with the definition of "full fatigue characterization" in the selection of partial safety factors, the following test shall be performed: cyclic fatigue test with more than one representative R ratio (typically at $R = -1$, $R = 10$ and $R = 0{,}1$).

Alternatively, the following inverse slopes of the S-N-curve may be used in combination with appropriate partial safety factors (γ_{m4}) for fatigue strength verification without further validation (static strength and assumed Wohler slope in fiber direction), provided that the fiber volume content does not exceed 55 % (glass fiber) or 60 % (carbon fiber; only tows ≤ 50 K):

- glass/epoxy laminates = 10
- glass/polyester laminates = 9
- carbon/epoxy laminates = 14

6.4.2.3 Structural adhesive and bonded joints

Bonded joint strength (ultimate and fatigue) shall be evaluated using representative tests consistent with the partial safety factors according to 6.6.5.8 and 6.6.5.9. Fatigue shall be evaluated using a reasonable spread of the number of cycles (e.g., 4 consecutive decades, with 3 samples in each decade). One of the decades shall exceed 10^6 cycles. The bonded joint strength may be evaluated using more complex and realistic details with correspondingly lower safety factors.

It is possible to employ a fracture based approach. In this case, the fracture toughness shall be tested and statistically derived characteristic values determined.

The following properties shall be established for the adhesive material:

- static tensile and shear moduli;
- state of cure (e.g., minimum glass transition temperature, T_g, for epoxy).

The following properties of the adhesive material should be tested, and a minimum criterion should be established as requirement for blade design and material selection:

- creep;
- shrinkage.

Adhesives should not have any adverse effects on the materials to be joined.

6.4.2.4 Sandwich structures

For compliance with lower γ_{m3} and γ_{m4}, the following core material properties shall be tested, and their statistically derived characteristic values for strength properties shall be obtained:

- out-of-plane compression (strength, modulus);
- maximum processing temperature.

In order to get the lower γ_{m3} and γ_{m4}, the following sandwich properties shall be tested, and their statistically derived characteristic values for strength properties shall be obtained:

- out-of-plane shear (strength, modulus, strain);
- peel or face sheet adhesion strength;
- face sheet wrinkling.

The sandwich panel materials shall be representative of the core material, face sheets and interface characteristics used in design of the blade. If core materials with slits, holes or scrim are used they also shall be included.

6.4.2.5 Structural metallic materials

The following material properties shall be tested for each material (or guaranteed through recognized standards):

- tensile strength;
- yield strength;
- elongation to failure;
- impact absorbing energy.

6.4.2.6 Surface finishes

The following material properties shall be tested and a minimum criterion established as requirement for material selection.

- adhesion to substrate (e.g., pull off tests);
- flexibility or elongation at break;
- erosion resistance against rain and particle impingement, for materials used on leading edge and tip areas.

It shall be ensured that the materials are sufficiently resistant to environmental influences, such as humidity and UV radiation.

The impact resistance (hail) should be tested and a minimum criterion established as requirement for blade design and material selection.

6.4.2.7 Non-structural materials

All non-structural materials (such as sealant, fillers, balancing weights, lightning protection system components, or other equipment) shall be documented. It shall be ensured that their properties are suitable for the intended purpose, that they can withstand the strains that result from the global blade deformation over the entire intended duration of operation and that they have no adverse effects on the blade structure.

6.4.3 Qualification of materials for manufacture

It shall be ensured that the material types used are meeting the design assumptions with regards to the material properties specified (and any additional tests used as a basis for the design).

The manufacturer shall define a qualification scheme for minor changes and materials delivered by new suppliers. The scheme shall identify requirements and test methods used to document that material meet the design and processing properties within the values and tolerances defined in the design.

The properties include strength and stiffness as well as manufacturing processing properties or characteristics that govern the material behaviour during manufacturing process. The relation between these material properties and process parameters (time, temperature, pressure, etc.) should be established.

In case of minor changes, such as those outlined below, a reduced set of tests is permissible:

- minor adjustments in raw materials as a part of the continuous development by the material supplier or shift to a new supplier of identical materials;
- minor changes in the production process (e.g., adjustments on curing cycle).

The blade manufacturer shall have specifications, applying to laminates or raw materials (e.g., resins, adhesives, fibers) in order to define critical parameters to test during qualification.

Specifications shall include but are not limited to:

- traceability of the materials;
- repeatability of material manufacturing processes;
- verification system (e.g., test methods) of incoming material properties;
- suitable material storage conditions.

6.5 Design for manufacturing

6.5.1 General

The design shall specify in the design documentation all requirements for the manufacture, necessary to meet the technical and functional specification and achieve the assumed structural integrity of the blade, including strength, stiffness, mass, mass moment, natural frequencies and stability.

Such requirements include specific manufacturing processes, materials, dimensions, tolerances and acceptance criteria for materials, geometries and assemblies.

Material coupon samples, elements and details, sub-components or assemblies tested for definition of design values (strength, stiffness and stability) shall be representative of the as-manufactured blade.

It is the responsibility of the blade manufacturer to validate any deviations from the baseline process. The manufacturer's production process shall avoid statistically significant changes to design values established using the baseline process.

Key tolerances, processes or product characteristics and acceptance requirements shall be defined by the designer or the manufacturer as critical-to-quality parameter (CTQs); see also 6.5.2. It is required that these CTQs are measured and recorded for each production build to ensure documentation for design or process compliance.

Other tolerances, processes or product characteristics and acceptance requirements shall be considered, and compliance with design or process shown by either continued recording, monitoring or demonstrated process capabilities.

The validity of safety analysis shall extend all the way to a product that can be manufactured and within a reasonable statistical certainty, maintain the calculated safety level. This may include the definition of manufacturing tolerances without direct effect on structural calculations. To account for such effect, a minimum list of required tolerances is defined below.

6.5.2 Requirement for manufacturing tolerances

Where applicable, the list of items for which tolerances and/or acceptance criteria for manufacturing that shall be defined in the design includes, but is not limited to:

- positioning of fabrics/layup in lengthwise and chord wise direction including length, width, overlap length and overlap shifts (staggering);
- orientation of fabrics/fibers (local and global);
- fiber misalignment (including wrinkles) – in plane and out of plane;
- fiber mat area weight;
- fiber volume fraction;
- distance between ply drop – including scarf joints;
- resin processing including mixing ratio and void content;
- resin cure level and process including temperature, time and vacuum level (if applicable);
- sandwich core material positioning (gaps, misalignment);
- sandwich core material dimensions (thickness, slitting/grooves, chamfering angle);
- positioning and orientation of prefabricated parts;
- glue filling (geometry and voids);
- glue mixing ratio;
- glue free edge shape;
- glue cure level and process including temperature, time and vacuum level (if applicable);
- bond line dimensions: thickness and width as well as maximum size and extent of permissible deviation (dimensions, voids, cracks, percentage of filling/coverage);
- bonding surface preparation and protection;
- coating quality – adhesion and thickness;
- temporary storage after surface preparation, before bonding;
- bolt holes position (deviation from nominal position);
- geometric positioning of assembled parts other than bonding major structural parts (incl. balance mass). Bolted connections shall have specified pretension;
- geometric positioning and diameter of drainage hole;
- electrical resistance of lightning protection system.

6.6 Structural design

6.6.1 General design approach

Subclause 6.6 provides requirements for the analytical and numerical design of a wind turbine blade structure. The integrity of the blade structure shall be verified, and an acceptable safety level shall be demonstrated. The ultimate and fatigue strength of the blade shall be verified by calculations and/or tests.

This document describes requirements following a deterministic approach, using the limit states design method according to ISO 2394.

Alternatively, use of a reliability based design with a probabilistic approach is acceptable and could lead to other safety factors than those prescribed in this code. If a reliability-based approach is taken, the risk of failure shall be defined and documented where ISO 2394 may be used as guidance. If a reliability estimate is used instead of the factor design in this code, then the reliability model shall as a minimum account for the variability and uncertainties described in this code by the partial safety factors.

Subclause 6.6 refers to verification according to the limit states design method.

For all limit state analysis defined in IEC 61400-1, loads are defined according to the following:

$$F_\mathrm{d} = \gamma_\mathrm{f} F_\mathrm{k}$$

where

F_d is the design value for the load;

γ_f is the partial safety factor for loads;

F_k is the characteristic value for the load.

According to IEC 61400-1, the following four types of analyses shall be performed where relevant for the limit state analysis:

- analysis of ultimate strength;
- analysis of fatigue strength;
- stability analysis;
- critical deflection analysis (including mechanical interference between blade and tower, etc.).

Additionally, inter fiber failure (IFF) shall be assessed for laminate verification. For this assessment, characteristic loads, F_k, may be used (i.e. γ_f = 1,0).

Each type of analysis requires a different formulation of the limit state function and deals with different sources of uncertainties through the use of safety factors. In the following clauses, the four types of analysis are described related to wind turbine blades.

The level of modelling and verification shall be adequate for the considered failure modes, material and structural detail.

In all verification analyses, structural models shall use mean values for material stiffness (modulus). Uncertainties in modulus will be accounted for by material partial safety factors as appropriate for the analysis type.

6.6.2 Structural analysis

6.6.2.1 Ultimate strength analysis

For ultimate strength analysis, the blade structure shall be verified for all relevant failure modes using design loads. This includes but is not limited to fiber and inter-fiber failure modes.

Inter-laminar failure, delamination or de-bond failure can occur between adjacent laminae, cores or adhesives due to out-of-plane shear stresses and out-of-plane normal stresses. These failure modes will typically appear at design details such as thickness transitions, bolt connections, adhesive bond joints etc., which should be accounted for.

Sandwich core material failure can occur due to tensile, compressive, and shear loading. These failure modes should be accounted for.

6.6.2.2 Fatigue strength analysis

All fatigue strength analysis shall be done using design values for loads.

The failure mode for fatigue is the local accumulation of damage (according to the applicable fatigue damage accumulation model) in excess of that permitted by the fatigue strength of the local material during a period that is less than the design life of the structure.

Linear damage accumulation in the fiber direction according Palmgren Miner may be used to obtain the total damage. In that case, a stress or strain based constant life diagram shall be constructed from the available characteristic S-N curves. The characteristic number of cycles to failure shall be extracted for each applied strain condition (amplitude and mean level) from the constant life diagram. The number of expected cycles to failure shall be found for the applied strains/stress.

Stress or strain based verification may be replaced by fracture mechanics methods.

Fatigue calculation may be based on damage equivalent loads, Markov matrices or load time series.

Fatigue strength analysis may be based on a damage-tolerant approach:

- It shall be demonstrated that damage due to a failure mode does not otherwise compromise the structural integrity of the blade (e.g., static failure, excessive deflection, etc.) during its design life.
- When a failure mode is evaluated to be acceptable, subsequent failure modes shall be assessed. Progressive development and interaction of failure modes shall be considered.
- If a particular failure mode in the failure sequence will compromise structural integrity, then the structure shall be designed in such a way that the preceding failure mode does not lead to progression.
- The damage tolerance of a sequence of failure modes shall be verified for both static and fatigue loading conditions.
- The damage tolerance of a sequence of failure modes shall be verified by either
  - progressive damage analyses validated by intermediate level testing or full blade testing, or
  - other justified method providing the same reliability level, including testing that demonstrates the alternative load path, based on assessment of failure modes.

6.6.2.3 Stability analysis

Global static instability (i.e., global buckling) occurs when a small increase in load results in a large and unstable increase in deformation, thereby limiting the capacity of the blade to carry any further load. It shall be demonstrated that global static instability does not occur at any load less than or equal to the product of the design load and the applicable combined factor of safety required herein. Nonlinear increases in the deformation of the blade in response to increases in load are permissible so long as the response remains stable, the blade does not lose its ability to carry further increases in load, and the nonlinear response does not induce damage in any structure due to other failure modes or result in excessive deflection of the blade towards the tower.

Local instability (i.e., local buckling) refers to a portion of a structural member (e.g., sandwich panel face sheet wrinkling or crimping) and shall be evaluated.

The verification of static stability shall be based on analytical or numerical methods, full scale testing or a combination hereof.

6.6.2.4 Critical deflection analysis

Deflection analysis shall be conducted according to IEC 61400-1, where also the relevant design load cases and partial safety factors are defined.

The value of γ_m for critical deflection analysis as defined in IEC 61400-1 shall be 1,1 to account for uncertainty in predicted global stiffness and blade to blade variation, if no other justification is done.

The value of γ_m may be reduced to 1,05 if the elastic properties are validated by a full scale blade test on the actual blade, the criteria of 6.6.3.2 are met without further justification, and monitoring is performed.

The value of γ_m may be reduced to values lower than 1,05 but not lower than 1,00 if the blade elastic properties consistency is demonstrated by statistics by blade deflection testing on multiple same or similar blade types indicating a better performance, and monitoring is performed.

Monitoring of elastic properties, consistent with IEC 61400-1, may be fulfilled by, but not limited to, the following methods:

- sample measurements on production components;
- testing on multiple same or similar blade types.

In all cases the value for γ_n shall be 1,0.

6.6.3 Verification requirements

6.6.3.1 Model resolution

The model used for blade structural analysis shall use as a minimum, the resolution in spanwise and chordwise directions as noted below:

- Spanwise resolution:

A sufficient number of spanwise sections shall be considered.

Verification shall include, at a minimum, 12 cross sections along the blade length (spanwise).

The spanwise distance between sections verified shall not be larger than 1 × the smallest chord length for the given section from root to largest chord.

For the sections from largest chord to 85 % of blade length the spanwise distance between sections verified shall not be larger than 2,0 × the smallest chord length for the section.

- Chordwise resolution:

A sufficiently detailed chordwise resolution shall be used for the modelling of each section. Resolution may be adapted to the verification performed.

6.6.3.2 Validation of global model by testing

When the design created in accordance with the requirements of this document is validated through a comparison with obtained results from full scale blade testing, the following applies as a minimum:

- comparison of calculated and measured values;
- assessment of the measurement results.

Deviations of at most ± 7 % for the global bending deflection at the outermost loading station, ± 5 % for the first natural frequencies in two main directions and ± 10 % for the axial strains are permissible without further justification at load levels of the testing performed in accordance with IEC 61400-23.

6.6.3.3 Validation of analytical models and methods

Models used and assumptions made during the analytical design affect the uncertainty of calculated results.

For individual analyses, the use of partial safety factors (PSF) account for such uncertainties. Validation of numerical/analytical models for a specific design may be based on an existing comparison between numerical/analytical modelling and test results applied to comparable design concepts. The selection of partial safety factors is dependent on extent of validation of the models. Correlation to a test using longitudinal gauges only permits reduction in PSF for laminate dominated by longitudinal loading consistent with the location of the gauges. The PSF for transverse or multi-axial load dominated structures remains at the higher level. For specific analysis and selection of PSF, a validation of the corresponding models applies. For FE- or similar numerical models the limits in 6.6.3.2 may be considered as criteria for compliance.

For validation of models using an existing correlation, the blade tested and used for comparison shall be of similar design, with sufficiently representative construction and loading to the blade being designed.

6.6.3.4 Intermediate level tests

Intermediate-level (e.g., elements and details or sub-component level per Figure 3) or full blade testing may be used to justify reduced PSF values. Such features include, but are not limited to: wrinkles, bond-lines, embedded studs, T-bolts, and ply drops.

In addition to providing a more accurate representation of blade details than coupon tests, intermediate-level testing enables a larger number of tests than is feasible in full blade tests, thus allowing for:

- statistically relevant data sets, with additional insight in the scatter of results;
- tests under various environmental conditions;
- comparative tests of various structural solutions.

To reach the lowest PSFs, the testing should ideally be performed based on the actual boundary conditions. However, simpler boundary conditions may be used to verify modelling results and gain the required confidence in the modelling.

6.6.4 Partial safety factors for materials

6.6.4.1 Definitions

The value of the partial safety factor for materials accounts for the inherent variability and uncertainties in FRP materials, laminated sandwich structures, bonded joints, methods and load resolution. To account for this, the material factors shall be specifically developed for each material type and combination of materials. This can be done either through a reliability-based dedicated test program or through an empirical approach. When using an empirical approach, appropriate partial safety factors shall be applied as follows:

$$\gamma_m = \gamma_{m0}\ \gamma_{m1}\ \gamma_{m2}\ \gamma_{m3}\ \gamma_{m4}\ \ \gamma_{m5}$$

where

γ_{m0} is the “base” material factor (to be included in all analyses);

γ_{m1} is the factor for environmental degradation (non-reversible effects);

γ_{m2} is the factor for temperature effects (reversible effects);

γ_{m3} is the factor for manufacturing effects;

γ_{m4} is the factor for calculation accuracy and validation of method;

γ_{m5} is the factor for load characterization.

The combined partial safety factor for materials in this document shall not be less than the minimum partial safety factor for resistance specified in IEC 61400-1.

The designer may define an alternative empirical approach (including relevant partial safety factors), provided the approach is justified through an appropriate verification which meets an equivalent level of safety and reliability to that achieved through the approach outlined in this document.

A reliability-based test program shall cover as a minimum the variables listed by the empirical approach adopted within this document and may be based on IEC 61400-1.

Values for each of the partial safety factors for materials are given in Subclauses 6.6.4.2 through 6.6.4.7 below. A general principle is that all failure modes and associated uncertainties in the transfer of material properties to the as-built blade shall be considered in the selection. Any adjustments of the partial safety factors γ_{m0} to γ_{m5} shall be documented by the designer and ensure an overall safety and reliability of the design comparable to the use of the values given below.

6.6.4.2 γ_{m0} Base material factor

For all strength and stability analyses, the base material safety factor γ_{m0} is:

$\gamma_{m0} = 1,20$

This factor covers uncertainties not covered by other safety factors.

γ_{m0} can be reduced to a minimum of 1,0 to compensate for $\gamma_n > 1,0$ such that the product of γ_{m0} and γ_n is 1,20.

6.6.4.3 γ_{m1} Factor for environmental degradation (non-reversible effects)

The partial safety factor for environmental effects accounts for the irreversible and long term degradation of the material properties compared to initial properties. The effects may include, but are not limited to:

- long-term degradation caused by temperature variation;
- chemical ageing and degradation;
- UV radiation (if applicable);
- humidity and salinity;
- external chemical influence;
- stiffness dependence on fatigue life;
- stiffness dependence on creep or strain relaxation.

The design shall specify the relevant environmental factors for the blade. If testing is performed, the testing of materials should be designed to cover the effects of these factors. Typical testing covers combined degradation effects of extremes of temperature and moisture, or long term effects of temperature variations.

6.6.4.4 γ_{m2} Factor for temperature effects (reversible effects)

The partial safety factor for temperature accounts for reversible and short term changes in material strength and stiffness properties with varying operational temperatures and their variability and uncertainties on the base laminate properties.

6.6.4.5 γ_{m3} Factor for manufacturing effects

For all verifications, the partial safety factor for manufacturing effects accounts for strength influence from the manufacturing tolerances and uncertainties of the as-built blade relative to the idealized structure or design values based on sub component or material specimen testing.

There are three elements to demonstrating manufacturing control:

- Determination of manufacturing tolerances. These may be drawn from best industry practice or determined specifically for the structure in question based on process validation and measurements. The reduced uncertainty that results from representative trials is reflected in the resulting PSF.
- Control of manufacturing CTQs. Specification during the design process of manufacturing CTQs that are measured and recorded for each production build results in reduced uncertainty. This includes material qualification and on receipt inspection.
- Material performance at tolerance limits. Characterization of the material and representative substructure performance at the limits of specified tolerances results in greatly reduced uncertainty. This is reflected in the PSF.

Tolerance stack-up shall be interpreted as the properties of the material at the limits of all the tolerances, not the product of individual knock-downs.

The analysis of manufacturing effects shall take into consideration the confidence level of the associated:

- inspection methods;
- manufacturing controls;
- manufacturing experience when documented by measurable process capabilities (duration, conditions, protection).

GUIDANCE – Variation impact analysis

This guidance section makes provision for the evaluation of identified critical manufacturing process robustness and repeatability within the blade design assessment.

For the determination of the level of γ_{m3}, the designer should specify the allowable tolerances in the critical manufacturing processes for a particular component or assembly and quantify their effects on the design properties.

This may require one, or a combination of more than one of the dominant tolerances to be considered.

In determination of the dominant tolerance for a particular manufacturing process, the designer should assess:

- likely variations (and magnitude thereof) to manufacturing process;
- detectability of variations;
- structural performance reduction due to variations.

If the designer wishes to adopt the lowest level of γ_{m3}, then verification of the structural performance shall be performed using a test program to determine material properties.

The test program shall utilize samples which embody maximum variations identified in the process assessment and loading regimes which represent the critical design conditions. It is not mandatory to verify by test the effect of every tolerance if there is sufficient evidence that some are not significant or can be assessed by analysis.

The analytical methods-based approach shall account for maximum variations identified in the process assessment and loading regimes which represent the critical design conditions. It is not mandatory to quantify the effect of every tolerance if there is sufficient evidence that some are not significant.

Table 1 below may be used as a template for identifying typical manufacturing effects (γ_{m3}) in relation to specific structural design verifications.

Table 1 – Typical manufacturing effects

Type of manufacturing tolerance to be evaluated: **for the verifications:**	**Fiber misalignment / orientation / wrinkles**	**Fiber volume fraction**	**Void content**	**Degree of cure / T_g Resin mixing ratio**	**Positioning (gaps, overlaps)**	**Bonding surface preparation and protection**	**Bond line thickness**	**Adhesive free edge shape**	**Adhesive open time**	
Laminate ultimate strength										
Laminate fatigue strength										
Inter fiber failure										
Sandwich core ultimate strength										
Global buckling										
Local buckling										
Bond ultimate strength										
Bond fatigue strength										

Mechanical fastening (ultimate and fatigue strength)										
Non-structural features										

END OF GUIDANCE

6.6.4.6 γ_{m4} Factor for calculation accuracy and validation of method

The partial safety factor for calculation methodology shall account for uncertainties related to the analysis methods used. The safety factor shall consider the accuracy of the analysis and the thoroughness of its verification.

In the case of laminate fatigue assessment, two components are considered in the factor for calculation and validation:

γ_{m4} is the product of γ_{m4a} and γ_{m4b}:

- γ_{m4a} factor for model validation: Correlation of predictive models used reduces uncertainty in the design.
- γ_{m4b} factor for fatigue model: Utilization of material fatigue properties supported by fatigue testing and more sophisticated damage accumulation models reduces uncertainty.

6.6.4.7 γ_{m5} Factor for load characterization

This partial safety factor accounts for uncertainties related to the resolution of, and combination of relevant applied load components.

In the simplest case, loads resolved into the positive and negative extremes of two perpendicular directions (e.g., minimum and maximum flatwise and minimum and maximum edgewise) for a total of four load sets may be applied individually.

Blade analysis incorporating intermediate load directions and combined loading events provide better representation and therefore justify lower partial safety factors.

In the case of laminate fatigue assessment, two components are considered in the factor for resolution of load components:

γ_{m5} is the product of γ_{m5a} and γ_{m5b}:

- γ_{m5a} is the factor for load direction resolution;
- γ_{m5b} is the factor for fatigue load formulation.

6.6.5 Structural design verification

6.6.5.1 Verification requirements

The following structural verifications shall be performed:

Laminate verification:

- laminate ultimate strength;
- laminate fatigue strength;
- inter fiber failure;
- sandwich core ultimate strength.

Stability verification:

- global buckling;
- local buckling.

Bonded joint verification:

- bond calculation ultimate strength;
- bond calculation fatigue strength.

Components:

- mechanical fastening ultimate and fatigue strength;
- non-structural features.

The detailed description of these verifications can be found in Subclauses 6.6.5.2 through 6.6.5.11.

6.6.5.2 Laminate ultimate strength verification

Factor	Values
γ_{m1}	**Factor for environmental degradation (non-reversible effects)** 1,20 – Material properties are based on room temperature, dry mechanical properties 1,00 – Material properties that take into account the relevant effects of environmental degradation
γ_{m2}	**Factor for temperature effects (reversible effects)** 1,10 – Material properties are based on room temperature 1,00 – Material properties tested to cover the extremes of the operational temperature range
γ_{m3}	**Factor for manufacturing effects** 1,30 – The blade analysis is performed using nominal design properties. The effect of dominant manufacturing tolerances on the design properties has been considered and shown appropriate within the safety factor used. 1,10 – The blade analysis is performed using design properties that include the quantified effect of the dominant manufacturing tolerances. The effect of these tolerances on the design properties has been verified by analytical methods and/or literature reference where applicable. 1,00 – The blade analysis is performed using design properties that include the verified effect of the dominant manufacturing tolerances based on process validation and measurements. The effect of these tolerances, including tolerance stacking, on the design properties have been verified by testing. In the case of wrinkles and ply drops, intermediate-level or full blade testing shall be used.
γ_{m4}	**Factor for calculation accuracy and validation of method** 1,20 – Strain calculation not validated 1,00 – Strain calculation validated by full blade test
γ_{m5}	Factor for load characterization 1,20 – Loads in 4 main directions 1,00 – Minimum 12 evenly distributed load directions

6.6.5.3 Laminate fatigue strength verification

Factor	Values
γ_{m1}	**Factor for environmental degradation (non-reversible effects)** 1,10 – Material properties are based on room temperature, dry mechanical properties 1,00 – Material properties that take into account the relevant effects of environmental degradation
γ_{m2}	**Factor for temperature effects (reversible effects)** 1,00 – No effect accounted for
γ_{m3}	**Factor for manufacturing effects** 1,30 – The blade analysis is performed using nominal design properties. The effect of dominant manufacturing tolerances on the design properties has been considered and shown appropriate within the safety factor used. 1,10 – The blade analysis is performed using design properties that include the quantified effect of the dominant manufacturing tolerances. The effect of these tolerances on the design properties has been verified by analytical methods and/or literature reference where applicable. 1,00 – The blade analysis is performed using design properties that include the verified effect of the dominant manufacturing tolerances based on process validation and measurements. The effect of these tolerances, including tolerance stacking, on the design properties have been verified by testing. In the case of wrinkles and ply drops, intermediate-level or full blade testing shall be used.
γ_{m4}	**Factor for calculation accuracy and validation of method** γ_{m4a}: Model (strain response to loads) validation 1,20 – Strain calculation not validated 1,00 – Strain calculation validated by full blade test γ_{m4b}: Fatigue model (Goodman or equivalent), based upon 1,20 – static strength and assumed Wöhler slope 1,10 – static strength and minimum one measured Wöhler slope 1,00 – full fatigue characterization (see 6.4.2.2) γ_{m4} is the product of γ_{m4a} and γ_{m4b}.

Factor	Values
γ_{m5}	**Factor for load characterization** γ_{m5a}: Factor for load direction resolution 1,20 – Bending moment spectrum evaluated on two main directions 1,00 – Bending moment spectrum evaluated on a minimum of six directions or strain spectrum evaluated from exact strain history (from time series) γ_{m5b}: Factor for fatigue load formulation 1,20 – Use of damage equivalent loads 1,00 – Use of full fatigue load description by e.g. Markov Matrix, time series γ_{m5} is the product of γ_{m5a} and γ_{m5b}

6.6.5.4 Inter fiber failure

Inter fiber failure (IFF) modes shall be considered for laminate and sandwich structures, based on characteristic loads F_k.

IFF can lead to subsequent premature fiber failure (both static and fatigue), as well as premature buckling failure.

Failure modes to be considered include IFF caused by in-plane transversal tensile or compressive stresses (σ_2), by in-plane shear stresses (τ_{12}), or a combination of these, and also as influenced by in-plane longitudinal tensile or compressive stresses (σ_1).

It shall be shown, by suitable means of verification that sufficient safety against the effects of IFF exists.

A suitable verification can consist of one or a combination of the three following:

1) Demonstration by analysis that matrix cracking does not occur for each individual layer of laminate

   The actual safety shall be documented in the analysis for ultimate strength by a failure hypothesis for anisotropic materials that is acknowledged in the literature, e.g., as per VDI 2014, Puck or Larc03. If a failure hypothesis as mentioned above is used, unless otherwise documented, the coefficients shall be included as follows:

$$p_{4\parallel}\ (-) = 0{,}25$$

$$p_{4\parallel}\ (+) = 0{,}3$$

   where $p_{4\parallel}$ (-) and $p_{4\parallel}$ (+) are the inclination parameters according to Puck.

   For the analytical verification, strength and strain design limits shall be based on average values from material testing.

Factor	Values
γ_{m1}	**Factor for environmental degradation (non-reversible effects)** 1,00 – No effect accounted for
γ_{m2}	**Factor for temperature effects (reversible effects)** 1,10 – For calculation performed by models using mean material modulus values valid for room temperature 1,00 – For calculations performed using mean material modulus values valid for the lowest operational temperature
γ_{m3}	**Factor for manufacturing effects** 1,10 – To be used for all analyses
γ_{m4}	**Factor for calculation accuracy and validation of method** 1,10 – For finite element (FE) analysis 1,20 – For other analytical models
γ_{m5}	**Factor for load characterization** 1,10 – Loads in 4 main directions 1,00 – Minimum 12 evenly distributed load directions

2) Demonstrate by analysis that matrix cracking is not critical to structural integrity

   Perform verification for laminate ultimate strength (see 6.6.5), laminate fatigue strength (see 6.6.5.3) and global stability (see 6.6.5.6) using design properties taking into account pre-damage by matrix cracking. This requires that all relevant material design limits are established through test coupons that have been subjected to load-induced matrix cracking prior to ultimate or fatigue failure test.

   The material test programme shall at least include, but not be limited to, the following:

   - UD and multiaxial fabrics ultimate tensile and compression with pre-damage induced by in-plane transversal tension and/or in-plane shear;
   - UD and multiaxial fabrics fatigue with pre-damage induced by in-plane transversal tension and/or in-plane shear.

   The pre-loading shall at a minimum be equivalent to the design ultimate strain or stress for the relevant material and direction.

3) Successful full blade test

   This test shall as a minimum include pre-fatigue static tests, fatigue tests and post-fatigue static tests according to IEC 61400-23.

   It shall be justified by analysis or other technical argumentation that areas with matrix cracking being a potential failure mode are sufficiently loaded.

   Inter fiber failures may be acceptable if these failure modes are understood and do not cause exceedance of other limit states.

6.6.5.5 Sandwich core ultimate strength verification

For ultimate strength verification of sandwich cores, the product of γ_{m0} and the factors γ_{m1} through γ_{m5} listed below shall be applied to the core material statistically derived characteristic strength values. The strength of the core material shall be demonstrated with respect to, but not limited to, minimum out-of-plane shear and crushing (i.e., compression normal the face sheets). In assessing the strength, local nonlinear deformations due to face sheet buckling shall be considered if appropriate.

Factor	Values
γ_{m1}	**Factor for environmental degradation (non-reversible effects)** 1,30 – Open cell foams, wood and honeycombs (allows ingress to core laminate interface due to temp variations) for which the material properties are based on room temperature 1,10 – Closed cell foams, wood and open cell foams with resin infusion for which the material properties are based on room temperature 1,00 – Material properties that take into account the relevant effects of environmental degradation
γ_{m2}	**Factor for temperature effects (reversible effects)** 1,20 – Material properties are based on existing literature or data sheets only 1,10 – Material testing is performed at room temperature 1,00 – Material properties tested to cover the extremes of the operational temperature range.
γ_{m3}	**Factor for manufacturing effects** 1,30 – The blade analysis is performed using nominal design properties. The effect of dominant manufacturing tolerances on the design properties has been considered and shown appropriate within the safety factor used. 1,10 – The blade analysis is performed using design properties that include the quantified effect of the dominant manufacturing tolerances. The effect of these tolerances on the design properties has been verified by analytical methods and/or literature reference where applicable. 1,00 – The blade analysis is performed using design properties that include the verified effect of the dominant manufacturing tolerances based on process validation and measurements. The effect of these tolerances, including tolerance stacking, on the design properties have been verified by testing. In the case of wrinkles and ply drops, intermediate-level or full blade testing shall be used.

Factor	Values
γ_{m4}	**Factor for calculation accuracy and validation of method** 1,35 – For analytical methods based on assumed or manufacturer’s unsubstantiated data and that have not been validated by intermediate-level or full blade testing. 1,20 – For finite element analysis based approaches using shell elements for panels combined with analytical expression for core strength failure mode, and the method of which has not been validated by intermediate-level or full blade testing. 1,20 – For computation using a finite element analysis using 3D elements for the core and that models geometric nonlinearities but that has not been validated by intermediate-level or full blade testing. 1,00 – For finite element analysis based approaches using shell elements for panels combined with analytical expression for core strength failure mode, the method of which has been validated by intermediate-level or full blade testing. 1,00 – For computation using a finite element analysis using 3D elements for the core and that models geometric nonlinearities, the method of which has been validated by intermediate-level or full blade testing.
γ_{m5}	**Factor for load characterization** 1,20 – Loads in 4 main directions 1,00 – Minimum 12 evenly distributed load directions

6.6.5.6 Global static stability (global buckling)

The designer shall verify through analysis that the blade does not lose its ability to carry load due to static instability at the design load with a combined safety factor equal to the product of γ_{m0} and the factors γ_{m1} through γ_{m5} listed in the table below.

The analyses shall be based on using statistically derived mean values of the material stiffness.

Thicknesses of sandwich cores shall be conservatively estimated, including potential compression related to the selected method of manufacturing.

The suitability of the FE mesh density shall be demonstrated by a convergence study. A sufficient accuracy of the mesh may be assumed when the (linear) buckling eigenvalue does not change by more than 5 % if the mesh density is doubled in the region of the model pertinent to the buckling mode in question.

For verification using linear methods of buckling analysis, it shall be demonstrated that the minimum eigenvalue corresponding to the first eigenform exceeds the required combined safety factor.

For verification using finite element analyses that model geometric non-linearity:

- The analysis shall demonstrate convergence when the combined safety factor γ_m has been applied to the design load.

- The load vector directions shall be considered and related to the deformation of the blade and consistent with the external loading.
- The FEM shall accurately reflect geometric imperfections related to validated production tolerance data. Alternatively, in the absence of validated production tolerance data, a stress-free pre-deformation proportional to the relevant linear buckling eigenforms (i.e., linear modes with an eigenvalue less than the required combined safety factor, including γ_{m4a} = 1,20) shall be applied to the structure with the height scaled to 0,25 % of the relevant eigenform wavelength. For the non-linear analysis in each load direction, a single pre-deformation may be formed from the superposition of the pre-deformations for the pertinent eigenforms associated with each independent linear buckling mode that does not fulfil the criteria for verification of static stability using a linear buckling calculation in that load direction.
- Nonlinear response shall not
  - result in failure of any structural member; all relevant failure modes shall be examined as per the remaining requirements of this document, appropriately accounting for nonlinear response;
  - occur at a load low enough to result in local fatigue damage, as per requirements elsewhere in this document;
  - result in excessive deflection of the blade as defined elsewhere in this document.

The term "independent linear buckling mode" is used to distinguish between buckling modes that appear at different locations on a blade and are due to distinctly different structural responses of the blade to a given externally applied load, in contrast to multiple modes emanating from a single location on the blade and reflective of a common structural response of the blade to the applied load. For example, in Figure 6, modes 1, 2, and 3 would be considered non-independent modes, while modes 1 and 20 would be considered independent of each other. The pertinent eigenforms that are included in the definition of the pre-deformation for each independent mode shall be selected to ensure that the full extent of the linear modes is addressed while ensuring that modes do not partly compensate for each other. If independent modes occur near each other, higher modes of each can overlap in a way that can obscure the independent nature.

Alternatively, the eigenforms associated with each independent linear buckling mode may be considered individually.

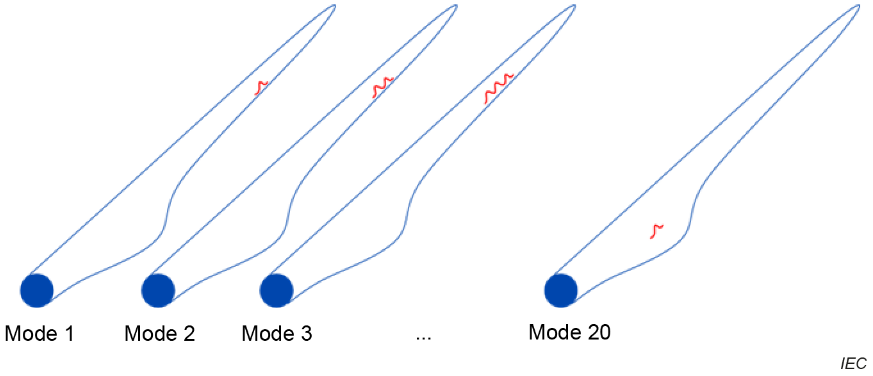

Figure 6 – Examples of Independent and non-independent linear buckling modes

Alternatively, the static stability of the blade may be verified through full scale testing. The test load used for verification shall equal the product of the design load and a combined safety factor equal to γ_m = 1,6.

Factor	Values
γ_{m1}	**Factor for environmental degradation (non-reversible effects)** 1,00 – No effect accounted for
γ_{m2}	**Factor for temperature effects (reversible effects)** 1,10 – When using core material modulus values at room temperature 1,00 – When using core material modulus values taking into account the highest operating temperature
γ_{m3}	**Factor for manufacturing effects** 1,00 – No effect accounted for
γ_{m4}	**Factor for calculation accuracy and validation of method** γ_{m4a}: Factor for analytical method 1,40 – For two-dimensional analytical methods (non FEA) 1,20 – For linear finite element analysis methods 1,00 – For computation using a finite element analysis that models geometric nonlinearities γ_{m4b}: Factor for validation 1,25 – For no validation 1,00 – For methods of which has been validated by intermediate level or full blade testing to non-linear buckling detection or failure γ_{m4} is the product of γ_{m4a} and γ_{m4b}.
γ_{m5}	**Factor for load characterization** 1,20 – Loads in 4 main directions 1,00 – Minimum 12 evenly distributed load directions

6.6.5.7 Local stability verification (face sheet buckling)

The analyses shall be conducted using mean values of the material stiffness.

For the static stability analysis, the partial safety factor γ_{m2} listed below may be applied to the material stiffness or to the load.

Nonlinear deformations that are stable are permissible so long as the deformations do not result in

- local static failure of either the face sheets or the core;
- delamination of the face sheets from the core;
- fatigue damage.

Factor	Values
γ_{m1}	**Factor for environmental degradation (non-reversible effects)** 1,00 – No effect accounted for
γ_{m2}	**Factor for temperature effects (reversible effects)** 1,10 – When using core material modulus values at room temperature 1,00 – When using core material modulus values taking into account the highest operating temperature
γ_{m3}	**Factor for manufacturing effects** 1,00 – No effect accounted for
γ_{m4}	**Factor for calculation accuracy and validation of method** 1,35 – For analytical methods based on assumed or manufacturer's unsubstantiated data and that have not been validated by intermediate-level or full blade testing. 1,20 – For finite element analysis based approaches using shell elements for panels combined with analytical expression for core strength and face sheet wrinkling failure modes, and not supported by validation testing. 1,20 – For computation using a finite element analysis using 3D elements for the core and that models geometric nonlinearities but that has not been validated by intermediate-level or full blade testing. 1,00 – For finite element analysis based approaches using shell elements for panels combined with analytical expression for core strength and face sheet wrinkling failure modes, the method of which has been validated by intermediate-level or full blade testing. 1,00 – For computation using a finite element analysis using 3D elements for the core and that models geometric nonlinearities, the method of which has been validated by intermediate-level or full blade testing.
γ_{m5}	**Factor for load characterization** 1,20 – Loads in 4 main directions 1,00 – Minimum 12 evenly distributed load directions

6.6.5.8 Bonded joint ultimate strength verification

This Subclause 6.6.5.8 covers the verification of the bonded joints for the ultimate strength state.

Design assessment of ultimate strength of bonded joints shall consider principal features of the joints such as the adhesive, bond line interface and inter-laminar loading of the adjacent substrate material and geometry. Features subject to inter-laminar loading not associated with a bonded joint shall also be handled in this Subclause 6.6.5.8. Adhesive joints comprising dissimilar substrates, such as composite to metal interfaces, shall also be handled with this Subclause 6.6.5.8.

Factor	Values
γ_{m1}	**Factor for environmental degradation (non-reversible effects)** 1,20 – Material properties are based on room temperature, dry mechanical properties 1,00 – Material properties that take into account the relevant effects of environmental degradation
γ_{m2}	**Factor for temperature effects (reversible effects)** 1,10 – Material properties tested at room temperature 1,00 – Material properties tested to cover the extremes of the operational temperature range
γ_{m3}	**Factor for manufacturing effects** 1,30 – The blade analysis is performed using nominal design properties. The effect of dominant manufacturing tolerances on the design properties has been considered and shown appropriate within the safety factor used. 1,10 – The blade analysis is performed using design properties that include the quantified effect of the dominant manufacturing tolerances. The effect of these tolerances on the design properties has been verified by analytical methods and/or literature reference where applicable. 1,00 – The blade analysis is performed using design properties that include the verified effect of the dominant manufacturing tolerances based on process validation and measurements. The effect of these tolerances, including tolerance stacking, on the design properties have been verified by testing.

Factor	Values
γ_{m4}	**Factor for calculation accuracy and validation of method** 2,00 – Analytical methods utilizing an average stress based failure criteria are employed to predict structure load carrying capability. The failure criteria used shall be based on the average bond stress of representative tests. Representative tests means similar interface materials, substrates and loading. 1,30 – A finite element model with stress based failure criteria is employed to predict structure load carrying capability. The model and failure criteria used shall be validated by representative tests. Representative tests means similar interface materials, geometry, model mesh refinement and ratio of peel and shear. 1,10 – A finite element model with fracture mechanics based failure criteria (such as interface elements or other analytical method) is employed to predict structure load carrying capability. Predictive capability shall be validated by representative intermediate-level or full blade tests. Representative tests means similar interface materials and ratio of peel and shear. Material properties shall be determined through suitable material tests. 1,00 – The characteristic strength for the as-manufactured bonding or detail has been established through an intermediate-level or full blade test performed such that the structure and loading are representative of the part being designed. It shall be shown by finite element analysis or similar method that the loading on the blade detail is lower or equal to the tested structures' characteristic strength with PSF applied.
γ_{m5}	**Factor for load characterization** 1,00 – No effect accounted for

6.6.5.9 Bonded joint fatigue strength verification

This Subclause 6.6.5.9 covers the verification of the bonded joints for the fatigue failure state.

Design assessment of fatigue strength of bonded joints shall consider principal features of the joints such as the adhesive, bond line interface and interlaminar loading of the adjacent substrate material and geometry. Features subject to inter-laminar loading not associated with a bonded joint shall also be handled in this Subclause 6.6.5.9. Adhesive joints comprising dissimilar substrates, such as composite to metal interfaces, shall also be handled with this subclause.

Factor	Values
γ_{m1}	**Factor for environmental degradation (non-reversible effects)** 1,10 – Material properties are based on room temperature, dry mechanical properties 1,00 – Material properties that take into account the relevant effects of environmental degradation
γ_{m2}	**Factor for temperature effects (reversible effects)** 1,00 – No effect accounted for
γ_{m3}	**Factor for manufacturing effects** 1,30 – The blade analysis is performed using nominal design properties. The effect of dominant manufacturing tolerances on the design properties has been considered and shown appropriate within the safety factor used. 1,10 – The blade analysis is performed using design properties that include the design effect of the dominant manufacturing tolerances. The effect of these tolerances on the design properties has been verified by analytical methods and/or literature reference where applicable. 1,00 – The blade analysis is performed using design properties that include the verified effect of the dominant manufacturing tolerances based on process validation and measurements. The effect of these tolerances, including tolerance stacking, on the design properties have been verified by testing.
γ_{m4}	**Factor for calculation accuracy and validation of method** 2,00 – Analytical methods utilizing an average stress based failure criteria are employed to predict structure load carrying capability. The failure criteria used shall be based on the average bond stress of representative tests. Representative tests means similar interface materials, substrates and loading. 1,30 – A finite element model with stress based failure criteria is employed to predict structure load carrying capability. The model and failure criteria used shall be validated by representative tests. Representative tests means similar interface materials, geometry, model mesh refinement and ratio of peel and shear. 1,10 – A finite element model with fracture mechanics based failure criteria (such as interface elements or other analytical method) is employed to predict structure load carrying capability. Predictive capability shall be validated by representative intermediate-level or full blade tests. Representative tests means similar interface materials and ratio of peel and shear. Material properties shall be determined through suitable material tests. 1,00 – The characteristic strength for the as-manufactured bonding or detail has been established through an intermediate-level or full blade test performed such that the structure and loading are representative of the part being designed. It shall be shown by finite element analysis or similar method that the loading on the blade detail is lower or equal to the tested structures' characteristic strength with PSF applied.

Factor	Values
γ_{m5}	**Factor for load characterization** 1,05 – Use of damage equivalent loads 1,00 – Use of full fatigue load description by e.g. Markov Matrix, time series

6.6.5.10 Mechanically fastened structural interfaces

6.6.5.10.1 General

Structural interfaces are connections between the wind turbine blade and distinct structural components such as the rotor hub structure, tip brake mechanisms, control surfaces or connections within the blade to facilitate a multi-part blade structure. These interfaces are usually comprised of two distinct materials (e.g., the composite blade structure and metal mechanical systems) that are joined using mechanical fasteners such as bolts or rivets.

For joints that rely on the combined effect of mechanical fastening and adhesion, each of the fastening methods shall be verified individually unless the load carrying capability of the combined system is demonstrated. Computational models of such interfaces may be validated through intermediate-level or full blade testing.

Strength verification of the structural interface may consider the following as a minimum:

- ultimate limit states;
- fatigue limit states.

Verification of interfaces shall account for the flexibility of the entire joint, including the fasteners and attached relevant structural components. Evaluation of pre-tensioned joints shall consider the potential for opening of gaps between the joined components. In situations where the thickness of the laminate is such that assumptions of plane strain/stress are not appropriate, the full 3D state of strain/stress shall be considered.

Strength verification of the mechanically fastened interface shall account for stress concentrations around holes in the surrounding material. Verification of the mechanically fastened interface shall furthermore consider the influence of specified tolerances on manufacturing and assembly (e.g., hole diameters, interface mating, tensioning and torqueing of fasteners, etc.). Verification of preloaded joints shall consider the long-term influences of stress relaxation and creep.

6.6.5.10.2 Blade root structure

The blade root structure where it interfaces with the rotor hub structure shall be analyzed using the same approaches defined for static strength, IFF, fatigue and adhesive bonds. However, special considerations shall be made to account for the influence of thick laminate and three-dimensional effects for which classical (thin) laminate analyses is not applicable. Furthermore, special attention to inter-laminar shear due to cleavage, wedge and other three-dimensional effects shall be considered. The complexity of the blade root end requires full blade and/or sub-component tests to determine the critical failure modes.

Tests shall be designed to capture the relevant failure modes for ultimate and fatigue strength. The geometry of the surrounding laminates shall be representative for the blade root connection. The test load levels shall be representative for the blade design.

Fatigue tests shall represent load introduction and load levels relevant for the blade design(s). Scaling of geometry and load cycles shall be verified and reported in the design documentation. Interpolation of test results to different geometries of the insert (e.g., diameter, length) shall be justified.

6.6.5.11 Non-structural features

Non-structural features are defined as items not directly contributing or affecting the load-carrying part of the blade, for example elements of the lightning protection system, anchor points (for fall arrest systems), aerodynamic devices (vortex generators, etc.), non-structural bulkheads and measurements systems.

Non-structural features do not include blade root interfaces, blade shell, web and spar structure, etc.

Where the failure of a non-structural feature can result in a safety risk for persons or property, a strength analysis shall be performed.

Verification methods and partial safety factors may be selected based on individual assessments, including considerations for safety for persons and property.

For all strength analyses, the minimum partial safety factor γ_m is:

γ_m = 1,20

6.6.6 Additional failure modes

6.6.6.1 Lightning

Wind turbine blades shall be designed against lightning strikes through the installation of a lightning protection system. The lightning protection system shall meet the requirements of IEC 61400-24.

6.6.6.2 Erosion

Wind turbine blades are vulnerable to erosion, in particular at the leading edge and tip. This erosion can be caused by environmental exposure such as rain, dust, and sand.

Relevant surface finishes should be evaluated for expected erosion, and the basis for erosion protection is to be specified for the blade.

If the blade utilizes anti-icing functions, the surface finishes should be evaluated against erosion for the maximum expected surface temperatures.

6.6.6.3 Other environmental effects

FRP materials are commonly sensitive to the direct exposures to external environmental effects such as moisture, foreign chemicals, and UV radiation. The blade design shall ensure that the structure is protected from these effects with an adequate environmental sealing system.

Materials should be selected that do not decompose chemically in the expected environment during the design lifetime. If this cannot be avoided, these effects should be quantified and considered in the development of the material’s characteristic strength.

The inadvertent exposure of materials to chemicals (such as hydraulic fluid) during maintenance activities should also be considered. If the exposure is considered significant, its effects should be considered in the development of characteristic strengths.

Some core materials may release gases over time, especially under high temperatures. The pressure build-up from these gases can cause core/skin delamination. This should be considered.

Corrosion of the constituent materials shall also be considered. Carbon fiber materials in contact with metals can lead to galvanic corrosion and the effects shall be considered.

Provision shall be made for the prevention of water accumulation in the blade.

7 Manufacturing requirements

7.1 Manufacturing process

The manufacturing process shall be suitable to meet the requirements defined in the structural design.

A risk assessment for each production step should be prepared (e.g., PFMEA process failure mode and effect analysis) including the effects of tolerances and acceptance criteria and their compliance with the structural design assumptions.

Critical and significant process parameters shall be identified. These shall be documented in a control plan or equivalent.

A process specification shall be established, including at least the following:

- description of successive manufacturing steps;
- description of successive quality control steps.

For each manufacturing step, a work instruction shall be established, including at least the following:

- detailed description of each action to be carried out, including sketches or photos if necessary;
- manufacturing drawings, clearly indicating dimensions, positions, and tolerances, for all individual elements (such as fiber material plies, or bond lines);
- materials to be used (bill of material);
- equipment and tools to be used.

A change management system shall be established to control, document and assure appropriate engineering evaluation of changes implemented in design, process and tooling specifications.

In Subclauses 7.2 through 7.8, required CTQs and requirements for process measurements and recordings are stated. Definitions of these are found in 6.5.1.

7.2 Workshop requirements

7.2.1 General

Manufacturers shall be suitable for the work to be carried out with respect to their workshop facilities, manufacturing processes, tools and equipment, as well as training and capabilities of the personnel.

Proof of this may be provided by means of a documented quality management system.

Where the requirements in this document will not ensure repeatability and product compliance with the design, necessary requirements shall be specified in the quality management system.

7.2.2 Workshop facilities

Workshop facilities shall be suitable for the work to be carried out.

Environmental requirements shall be defined for all areas where material processing or storage takes place. These requirements shall be monitored and recorded by local measurements.

For laminating workshops, if no other temperature and humidity values have been defined and documented as acceptable for the manufacturing process, a shop room temperature between 16 °C and 30 °C with a maximum relative humidity (RH) between 20 % and 80 % RH shall be maintained when materials are exposed to atmosphere. If the manufacturers of the laminating resins or adhesives have specified other processing temperatures and humidity, these should apply.

The provision of ventilation supply and exhaust equipment shall be such that an impairment of the materials is excluded, e.g., no unacceptable amounts of solvent are extracted from the laminate.

The danger of contamination of materials for laminating shall be kept to a minimum by separation of production areas and other workshops as well as storage rooms.

The workplaces shall be illuminated in a suitable manner. Precautionary measures shall be taken to prevent the uncontrolled curing of the resin due to illumination.

For specific work processes additional requirements may apply, and shall be stated.

As a minimum, the following CTQs shall be specified and recorded:

- shop room temperature and humidity shall be recorded continuously, according to QM specifications.

7.2.3 Material handling and storage facilities

Reactive materials, such as laminating resin compounds, prepregs, gelcoat, paint and adhesives shall be transported and stored according to the manufacturer’s instructions. The temperature and humidity in the storage and process areas shall be recorded continuously.

Reinforcing materials, core materials, fillers and additives shall be stored in closed packages, in such a way that contamination and environmental degradation (e.g., caused by dust, temperature, humidity, etc.) is prevented. Moisture sensitive materials exposed to air humidity shall be stored in spaces with continuous moisture recordings and humidity shall not exceed limitations specified for such materials unless the effect of such exceedance is insignificant.

Storage shall be arranged in such a way that the designation of the materials and the storage conditions and maximum storage periods (expiration dates) prescribed by the manufacturer, are easily visible. Materials whose shelf life has been exceeded shall be marked as being out of conformity and prohibited for use, unless proven and documented that the material is fit for specific purpose.

All materials sensitive to humidity to be processed shall remain with the packaging sealed when brought to the processing rooms, until their temperature will prevent condensation (reaching the dew point).

Reactive and moisture sensitive materials stored in packages removed from storage and opened may be returned to storage only in defined cases (e.g., hot-curing prepregs). The packages have to be clearly designated in such case.

Storage and handling of all materials (including auxiliary materials) which may have an impact to quality of any component should be considered.

7.2.4 Tools and equipment

7.2.4.1 Moulds and tooling

Molds and tooling equipment shall be suitable for the manufacturing process used.

Molds and tooling that provide final geometry of the blade shall be validated for compliance with functional requirements.

This includes, but is not limited to:

- temperature distribution during process (if applicable);
- surface roughness;
- surface waviness;
- geometry including tolerances.

7.2.4.2 Maintenance

A maintenance plan shall be defined for all tools, molds and equipment (excluding generic hand tools, etc.).

The maintenance plan shall specify by time intervals, process cycles or equivalent valid definitions for inspections and acceptance criteria.

In order to trace inspection/maintenance, tools and equipment that shall be marked with unique identification includes, but is not limited to (if applicable):

- all molds for laminating work;
- automatic process equipment for mixing liquid raw materials;
- drilling machine for blade connection;
- assembly jigs and fixtures.

The process for maintenance shall be described in the QM system.

7.2.4.3 Calibration

Measurement equipment used in the manufacturing process, including mixing equipment (e.g., flow measurement devices) for liquid raw materials, shall be subject to scheduled calibration.

The list of measurement equipment to be subject to scheduled calibration includes, but is not limited to:

- temperature and humidity sensors;
- dimension and angle measuring equipment (e.g., calipers, tape measure, laser measure);
- pressure sensors (if critical to process);
- mass measuring equipment (e.g., scales/load cells);
- dispensers/flow sensors.

Equipment shall be marked with a traceable label which includes the next required calibration date.

The process for calibration shall be described in the QM system.

7.2.5 Personnel

7.2.5.1 Training and qualification

The personnel assigned to blade manufacturing shall be sufficiently qualified.

Personnel performing or controlling critical work processes that directly or indirectly are influencing the structural integrity, including material properties, shall be qualified for such work.

Training and competence requirements for critical processes shall be defined.

Critical processes are defined as, but are not limited to:

- lay up of fiber reinforcement material, including prepregs;
- lay up of sandwich core materials;
- lay up of wood parts;
- installation of sub components;
- application of resin and glue;
- manual mixing of two or multiple component materials;
- application of gelcoat or paint;
- cutting, drilling or grinding structural materials;
- welding;
- NDT processes;
- QC including visual inspections.

Training level and competencies shall be documented for each employee performing or controlling critical work processes and be subject to regular reviews in accordance to the manufacturer’s quality management system.

7.3 Quality management system requirements

A quality management (QM) system that as a minimum meets the requirements in the ISO 9000 series standard shall be implemented by the manufacturer.

It is the obligation of the manufacturer to fulfill the manufacturing requirements laid down in this document and to include them in the QM system.

As a minimum, the QM system shall meet the requirements of the QM model according to ISO 9001. The QM system shall be defined in detail in writing.

Other standards may be used as reference for the QM system. The requirement regarding detail levels and documentation shall be comparable to those requirements specified in ISO 9001.

7.4 Manufacturing process requirements

7.4.1 General manufacturing requirements

In Subclauses 7.4.2 through 7.4.12, basic requirements for manufacturing processes typically used in blade manufacturing are given.

Any manufacturing process external to normal processes (such as maintenance, repairs) should be avoided during normal processes. If a process needs to be interrupted (i.e. weekend), actions should be taken such that there is no adverse effect in the final product due to the interruption.

Contamination from external factors that could affect a process (e.g., dust, paint, and spray in laminating/gluing area) should be taken into account.

Operation of dust-generating machinery, painting or spraying work is only permissible within the laminating workshop if the manufacturer can ensure that such activities will not negatively affect the laminating quality.

For the preparation and processing of materials, the instructions of the material manufacturer plus any other applicable regulations, such as those of the relevant safety authorities, shall be observed in addition to this document.

7.4.2 Gelcoat application to the mould

If surface finish is to be achieved by means of a gelcoat, the gelcoat shall be mixed and applied on the mold in accordance with the process specification, using a suitable process.

Curing level and/or allowable time range for application of the first layer of laminate to the gelcoat shall be specified.

As a minimum, the following CTQ shall be specified and recorded:

- thickness of the gel-coat (wet or dry).

7.4.3 Building up the laminate

7.4.3.1 General

The laminate shall be built up in accordance with the process specification.

For sandwich core materials, it shall be ensured that the conditions of the material during processing are defined and controlled. This may include, but is not limited to, degassing, tempering and controlling humidity.

Extension of layers (creating a joint when fiber length/roll is insufficient) may only take place if described in work instructions.

Pre-shaped components such as wood or foam kits, fiber stacks, etc. shall be specified and processed in a way ensuring repeatability.

Controls shall be in place such that prefabricated components incorporated into the laminate do not adversely affect the overall structure.

As a minimum, the following process parameters should be specified, controlled and/or monitored:

- gaps and steps in between adjacent core segments;

- position of layers, including overlap between layers;
- alignment of fibers.

7.4.3.2 Consolidation of the laminate

The layers shall be adequately consolidated and compressed so that subsequent process requirements are met.

7.4.3.3 Application and curing of resin

It shall be documented that the process can produce the specified design within the acceptance criteria, including dry areas or air content and within fiber volume or mass fraction percentage as defined in material requirements to meet design strength values.

The application process shall be suitable for the resin system used.

Resin and reaction agent shall be mixed homogeneously and without any intrusion of air. If mixing machines are used, a procedure to verify and control the correct mixing ratio for each manufacturing cycle shall be defined.

Hand layup processes (such as resin mixing, mechanical preparation (rolling) to release trapped air or other gasses in the laminate, and cure) shall be controlled such that the specified final laminate quality is ensured.

During production, the processing time for the mixed resin compound specified by the manufacturer shall not be exceeded. In the absence of such information, the pot time shall be established in a preliminary test and the processing time limits described in the manufacturing specification.

Controls shall be in place such that prefabricated components incorporated into the laminate do not adversely affect the overall structure.

If vacuum assisted consolidation is required, the allowable process temperature and vacuum level, both as function of time, shall be defined.

For resin infusion, the relevant processing parameters shall be specified, at least including resin application temperature and time, vacuum set-up, as well as level of applied differential pressure for infusion and cure.

Inspection methods shall be defined for laminate imperfections (e.g., void content, dry laminates, inclusions, high or low resin content).

As a minimum, the following process parameters should be specified, controlled and/or monitored:

- cure cycle, resin temperature and vacuum level during cure and/or infusion process;
- time from mixing resin to complete application.

7.4.4 Adhesive bonding process

7.4.4.1 Surface preparation

The surface treatment procedure before bonding shall be specified. The process for preparation of surfaces to be bonded shall be suitable for the substrates and adhesive material used.

Typical surface treatment procedures may include mechanical roughening (e.g., rough-grinding, grit or sand-blasting, removal of peel-ply) and chemical etching.

Surface preparation degradation (e.g., moisture and dust accumulation, time elapsed between surface treatment and bonding, and environmental conditions) shall be considered.

Acceptance criteria for surface condition before bonding shall be specified with respect to dust and surface contamination and meet the requirements for the specific adhesive used.

If required by the adhesive type, the surfaces of the materials to be bonded together shall be free of contaminants (e.g., moisture, release agents, wax, grease, oil, dust, rust, or solvents). When using solvents for cleaning purposes, compatibility with the material shall be ensured.

If FRP components are to be bonded, minimum and maximum curing level before bonding shall be specified.

7.4.4.2 Application of adhesive

The processes for mixing and application of the adhesive shall be suitable for the substrates and adhesive material used. Procedures to control and verify the correct mixing ratio shall be defined. Processes shall be controlled such that the specified final adhesive properties are achieved.

The nominal values and tolerances of adhesive-layer width and thicknesses, as well as the maximum size and extent of permissible variations (e.g., voids, fillet radii), shall be defined.

The adhesive shall be processed in accordance with the manufacturer’s instructions. The proportion of fillers may not exceed the permitted limit. The adhesive shall be mixed in such a way that a homogeneous mixture is achieved.

The time from mixing of the adhesive until end of application and final joining of the parts in the correct position shall be specified and recorded, taking into account environmental conditions.

7.4.4.3 Quality assurance

Compliance of the bond line geometry with design specifications shall be ensured. This may be achieved either through use of a controlled process with demonstrated stability or by inspection of each part. For example, mold dry closure test (joining the parts without permanent bonding in order to verify bond thickness or gaps), visual inspection, and/or NDT measurements may be used to show compliance with manufacturing requirements.

As a minimum, the following process parameters should be specified, controlled and/or monitored:

- bond width;
- bond thickness;
- cured adhesive hardness;
- mixed adhesive viscosity;
- void content;
- open time for surfaces prior to bonding;
- time from start of mixing adhesive to complete joining of parts.

7.4.5 Curing

Resin and adhesive systems shall be cured such that the required final properties as defined in design specifications are achieved. This may include curing in accordance with the resin or adhesive manufacturer’s instructions or the results of suitable previous investigations. This requirement includes post-curing operations.

Cure time-temperature profiles shall be controlled and recorded such that design properties of the adhesives and resins are achieved. Tolerances on these profiles shall be defined.

Cure of resins and adhesives shall not adversely affect blade components. For example, maximum temperatures occurring during cure should not exceed the maximum allowable temperature for PVC foam or tooling materials.

A sufficient degree of cure shall be achieved before proceeding with operations (e.g., demolding or blade/prefabricated component movement) that would result in damage to structures.

The degree of cure shall be verified and documented.

As a minimum, the following process parameters should be specified, controlled and/or monitored:

- degree of cure, if applicable.

7.4.6 Demoulding

The demolding process of the blade or blade components shall be defined and described.

7.4.7 Trimming, cutting, and grinding

Trimming, cutting, and grinding processes include all operations that will mechanically remove material. This includes, but is not limited to:

- drilling holes in the structure;
- milling the root face;
- trimming and cutting excess material resulting from laminating processes;
- sanding and grinding operations.

Trimming, cutting, and grinding processes shall be defined such that the blade structure is not degraded by the processes and that critical dimensions meet design criteria.

7.4.8 Surface finish

Surface finish may include painting (including primer/paint systems), gelcoat, and leading edge protection.

For the application of surface finishes (except gelcoat), the application process and surface conditions shall be specified.

The primer or paint mixing process and the application processes shall be controlled in accordance with the process specification and shall be suitable for the materials used. Processing parameters and tolerances shall be defined, controlled, and documented to meet design requirements, including but not limited to mixing ratio.

The finish process shall provide the required adhesion between the finish and structural laminate. Curing level and/or time allowable range for application of the finish to the laminate surface shall be specified.

Thickness of finishes shall be specified with tolerances either before or after curing. Measurements of thickness shall be recorded evenly over the blade surface.

If applicable, leading edge protection systems (LEP) and their application processes shall be specified. Processing parameters and tolerances for LEP shall be defined, controlled, and documented to ensure the final LEP meets specified requirements.

As a minimum, the following process parameters should be specified, controlled and/or monitored:

- surface finish: gloss, color, roughness;
- level of cure;
- surface coating thickness.

7.4.9 Sealing

Unless demonstrated to be not necessary, laminate surfaces without surface protection shall be sealed using suitable agents. In particular, the cut edges of cut-outs and glued joints shall be carefully protected against environmental effects (e.g., moisture or UV radiation).

The sealing materials used shall not impair the properties of the laminate. They shall also suit the intended purpose of the component.

7.4.10 Additional component assembly processes

If in workshop assembly or installation of sub components or additional features takes place, this shall be described in work instructions including geometric positions and process or torque values with tolerances. This includes, but is not limited to:

- root connection parts;
- blade bearings;
- blade root bolts;
- lightning protection system components;
- drainage systems;
- mechanical tip brake systems;
- joints in segmented blades;
- aerodynamic devices (e.g., vortex generators).

7.4.11 Mass and balance

The balancing process including the use of equipment, handling and installing balancing material shall be specified in work instructions.

Features or equipment which is not part of or added after the balancing process, shall be quantified and included in the blade documentation.

As a minimum, the following CTQ shall be specified and recorded for each blade after balancing:

- blade total mass;
- blade center of gravity position or blade mass moment (including reference position);
- the balance weight added (for each balancing location if applicable).

7.4.12 Manufacturing and assembly processes outside controlled environment

Any manufacturing or assembly process taking place outside controlled environment shall be considered for sensitivity to external climatic conditions. This applies to work performed outdoor etc.

If these operations outside controlled environment are considered as part of the standard manufacturing process (e.g., scratch repair after blade transportation, cleaning surface before blade erection) they should be documented and demonstrate that they will not affect any of the design requirements or performance of the blade.

Materials should be specified to be compatible with the new environmental condition as well as compatibility with the standard materials used in the workshop.

For laminating or bonding processes, the environmental limitations shall be defined for minimum the following parameters:

- temperature;
- humidity;
- wind speed;
- surface preparation and contamination.

Condensation on material surfaces due to temperature and dew point shall be considered.

7.5 Manufacture of natural fiber-reinforced rotor blades

The mechanical properties for natural fibers (including wood, bamboo and other naturally-grown fibers) may be more sensitive to the processing. Processing parameters and limitations shall take this into account.

For natural fiber materials, the requirements of the species, producing area and age of the raw materials should be clearly defined. If relevant to the material, pre-sorting shall be used to ensure that the material meets the required quality standard. Moisture contents shall be defined and controlled to ensure that laminated materials meet the documented requirements prior to and during processing.

Qualification of materials for the manufacture shall take into account the additional variability of mechanical properties for strength, stiffness and density of natural fibers.

For characteristics regarding natural fibers not covered in this document, alternative industrially accepted standards can be adopted.

7.6 Other manufacturing processes

For other manufacturing processes not covered under Subclauses 7.4 and 7.5 (“Manufacture of fiber reinforced blades” or “Manufacture of natural fiber reinforced blades”), it shall be ensured that similar documentation and quality level as described for fiber reinforced material processes or natural fiber processes is documented.

7.7 Quality control process

7.7.1 Manufacturing quality plan

A manufacturing quality plan shall be defined with list of inspections and documents for each manufacturing step.

7.7.2 Incoming inspection

The manufacturer shall establish incoming inspection procedures, including applicable methods, to ensure that materials and components that are used in the manufacturing process comply with the properties and tolerances, defined in the design or material specifications.

Incoming materials inspection shall include, but is not limited to:

- structural fiber reinforcements;
- structural resins;
- structural adhesives;

- prepregs;
- gelcoat and paint;
- structural core materials;
- structural bolts and fasteners, including root inserts.

Methods for incoming materials inspection could include:

- incoming inspection certificates;
- verification by suppliers documented quality control procedures;
- internal checks for any damage;
- specified internal testing with defined sampling rate or frequency.

Acceptance criteria for these methods shall be defined in the documentation.

Incoming inspection certificates may be based on ISO 10474-2.2 (EN 10204-2.2) and ISO 10474-3.1 (EN 10204-3.1) in connection with ISO 10474 (EN 10204), or equivalent alternatives.

7.7.3 Manufacturing and quality control records

Details of the production process shall be laid down by specifications and work instructions, which also contain documents for the recording of selected production process parameters, e.g., CTQ values, testing of the components.

The tasks and responsibility of the production and quality control departments shall be defined clearly, including competences for signing off process and quality documents.

At defined stages in the process, completion of the step is confirmed and checked by competent persons as prescribed in the quality plan.

The following data shall be recorded for each blade produced and stored in a secure location for the design life of the blade:

- blade serial number or similar unique identification;
- all critical to quality (CTQ) process and design items as measured or recorded during in-process checks, approvals and inspection lists, and the corresponding limits;
- record of non-conformance reports (NRCs) and disposition/repair;
- batch numbers for materials with required traceability;
- identity (serial number or equivalent) of blade tooling used which affect CTQs.

Traceability of raw material (i.e. supplier, batch and lot numbers) used in the component shall be ensured for minimum the following items:

- structural fiber reinforcements;
- structural resins;
- structural adhesives;
- prepregs;
- gelcoat and paint;
- structural core materials;
- structural bolts and fasteners.

For other manufacturing processes using materials not covered by the above descriptions, it shall be ensured that similar documentation and quality records are documented.

7.7.4 Non-conformity process

7.7.4.1 Non-conformity identification and recording

A system to record and evaluate any non-conformity observed during manufacture shall be established (e.g., as part of a QM system according to ISO 9001).

It shall be ensured that non-conformities in manufacturing (e.g., exceedance of tolerances or acceptance criteria) are detected and documented.

7.7.4.2 Non-conformity evaluation and correction

A procedure for evaluation of corrective actions shall be established. Non-conformity shall be classified by severity and need for corrective action.

The severity shall be evaluated in compliance with the structural requirements of Clause 6.

Corrective action including structural repairs shall be categorized depending on structural severity, this should include the designer.

If corrective actions include acceptance or standard repair of non-conformities, this shall be taken into account in the design documentation.

7.7.5 In manufacture corrective action processes

For in-manufacture corrective actions, it shall be ensured that the resulting structure and geometry complies with the requirements of Clause 6.

For corrective actions including structural repairs, this compliance shall be demonstrated by the following means:

- full description/specification of the repair (preparation, materials, lay-up, processes etc.);
- design analysis according to the requirements of 6.6. This analysis shall include an explicit specification of the partial safety factors applied for the repaired structure. It is permissible to use partial safety factors different from those applied in the analysis of the unrepaired structure, provided that the conditions for the application of these factors as per 6.6.5 are fulfilled;
- full documentation of the repair performed (manufacturing protocol).

Structural repairs include but are not limited to:

- cutting, grinding and/or replacement of any continuous fibers;
- removal and/or replacement of any structural adhesive;
- removal and/or replacement of sandwich core material.

Non-structural repairs may include:

- paint or gelcoat repairs;
- minor filling of surface to meet geometry requirements;
- replacement of lightning protection parts.

7.7.6 Final manufacturing inspection and conformity review

A final inspection shall be carried out by the manufacturer.

The inspection procedure shall be specified and shall include, but is not limited to, the items below:

- check of the geometry including accuracy of profile data and trailing edge thickness;
- determination of the mass and the center of gravity;
- check of the balance quality for each set of blades;
- surface quality and appearance;
- drainage system (if applicable);
- functional checks of installed systems (to include – but not limited to)
  - brake system,
  - flaps or moving devices,
  - sensors and monitoring system,
  - lightning protection system;
- work progress sheets and check sheets which accompany the rotor blade through the production process;
- Completeness check of the data and entries in control sheets and inspection lists. Verification of data (CTQ) compliance with acceptance criteria.

Data and conclusions from final inspection shall be recorded and stored with blade manufacturing documentation.

7.7.7 Documentation

7.7.7.1 Identification marking of blades

Each rotor blade shall be permanently marked with a unique identity reference.

The unique identity can be by serial number and shall allow identification of production location and blade manufacturing documentation.

Furthermore, a permanent identification (e.g., a plate from non-corrosive material) shall be attached in an easily accessible position with at least the following information:

- manufacturer;
- type designation;
- serial number.

A reference for pitch setting angle shall be marked on the blade root, unless by the design this is defined by other means.

7.7.7.2 Blade documentation

The final inspection/check shall be documented.

The documentation shall contain minimum the following data for each rotor blade:

- manufacturer;
- rotor blade type designation (e.g., model/name);
- serial number and date of manufacture;
- mass and centre of gravity;
- mass moment (including geometric reference);
- type of aerodynamic brake, if applicable.

7.8 Requirements for manufacturing evaluation

The manufacturing evaluation shall include spot checks of the manufacturing processes critical to the material structural properties, including:

- layup of main structural fibers, core materials and/or components;
- resin application processes (if applicable);
- main bonding processes (if applicable) including surface preparation, positioning of components and glue application.

Special attention to quality procedures related to critical processes shall be made, including:

- cure processes.

As a minimum, the following documents shall be reviewed for compliance with the design and be available for the performance of the manufacturing evaluation audit.

- material qualification;
- work instructions and drawings, including process specifications with tolerances;
- quality control sheets, including acceptance criteria/tolerances for CTQ's.

Requirements for the quality management system in relation to manufacturing evaluation as per 7.3 shall be met.

8 Blade Installation, operation and maintenance

8.1 General

Clause 8 defines requirements for information and requirements to be provided for safe handling, operation and maintenance of the blade.

The operational limits and ranges for the blade shall be defined.

Requirements needed for fulfilling conditions or assumptions in the blade design shall be specified and made available in the form of information material (e.g., manuals or similar) for persons handling, operating and/or performing maintenance of such blade, for the complete design lifetime.

The designer shall consider the need for any personal protection equipment, relevant for specified maintenance work.

8.2 Transportation, handling and installation

Manuals shall include, but is not be limited to, instructions for lifting and handling, transportation and storage procedures.

Guidelines shall be provided which define all the work related to blade handling, including but not limited to lifting, storing, transporting and mounting.

If lifting and handling is limited by design to specific areas on the blade, the dimensions and position of such areas that are specified for use in lifting and handling the blade shall be included in the manual.

Location and reference (e.g., on the blade by a sticker, sketch or an attached instruction) shall be provided for:

- the centre-of-gravity (CG);

- dimensions and position of areas that are specified for use in lifting, handling and storage.

Allowable handling procedures shall define:

- the orientation of the blade during lifting and handling (e.g., flatwise or edgewise);
- which combinations of lifting locations can be used together;
- how blades shall be rotated;
- how to achieve protection of the whole blade, but in particular the leading and trailing edges;
- how to support and secure blades during storage and any applicable time limitations for storage.

Allowable maximum accelerations and loads during transportation shall be defined for the blade.

The dimensions and position on the blade of areas that allow for support during transportation and storage of the blade shall be clearly marked.

If transportation fixtures are mounted on the blade root using blade installation connection, the minimum number of bolts and the tensioning procedure shall be specified.

8.3 Maintenance

8.3.1 General

Inspection and maintenance requirements for lightning protection systems shall be described according to the requirements in IEC 61400-24.

If the blade design requires any further routine maintenance or inspections, this shall be specified.

If procedures for blade cleaning are prescribed, acceptable means of cleaning process including any limitation in the use of chemicals, shall be stated.

A blade maintenance manual may describe defects that are acceptable for safe operation. If such defects are described and may cause structural degradation, then these shall be considered in the design and/or testing.

8.3.2 Scheduled inspections

If scheduled inspections are required, the following shall be specified:

- the type of inspection, along with its intervals and timing;
- the blade areas to be inspected;
- applicable acceptance criteria.

Typical inspection locations may include but are not limited to:

- trailing edge;
- leading edge;
- spar cap;
- root connections/root seals;
- blade tip/drain holes;
- lightning protection systems and recorders;
- blade panel surfaces;

- internal areas, e.g., shear webs;
- blade mechanical systems, e.g., tip brakes.

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

3, rue de Varembé
PO Box 131
CH-1211 Geneva 20
Switzerland

Tel: + 41 22 919 02 11
info@iec.ch
www.iec.ch