

INTERNATIONAL STANDARD

NORME INTERNATIONALE



**Wind energy generation systems –
Part 5: Wind turbine blades**

**Systèmes de génération d'énergie éolienne –
Partie 5: Pales d'éoliennes**



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IEC Central Office
3, rue de Varembe
CH-1211 Geneva 20
Switzerland

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

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Part 5: Wind turbine blades**

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

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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.

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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)

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

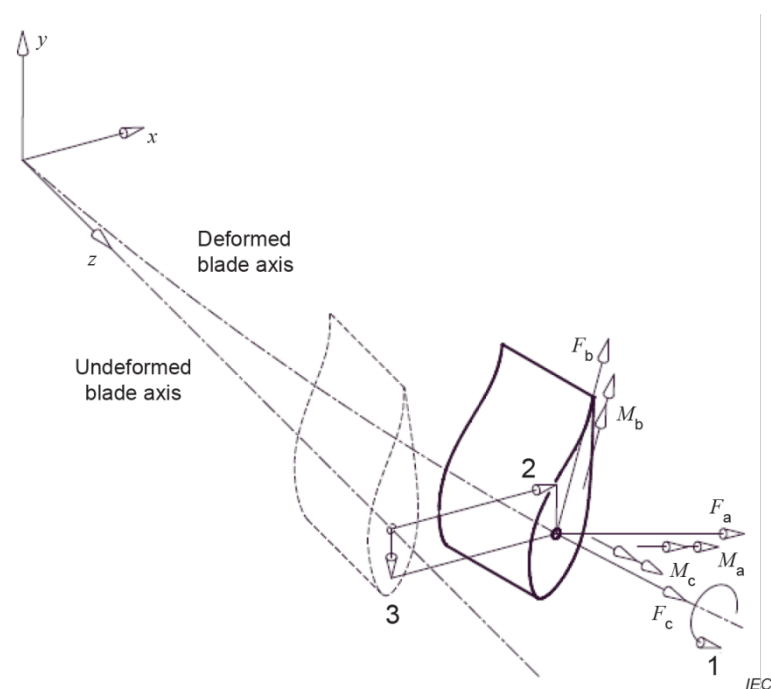
m5 materials for load characterization

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

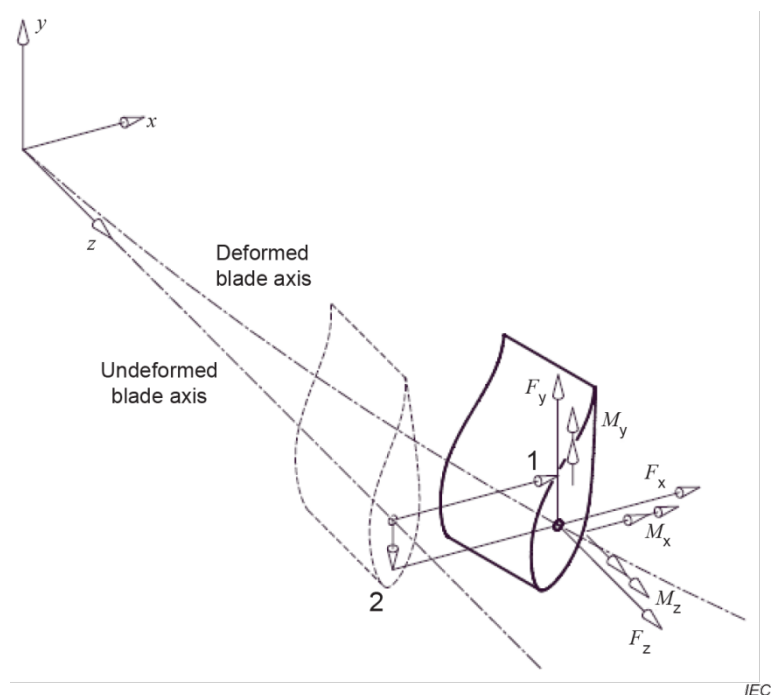
F_c axial force

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.

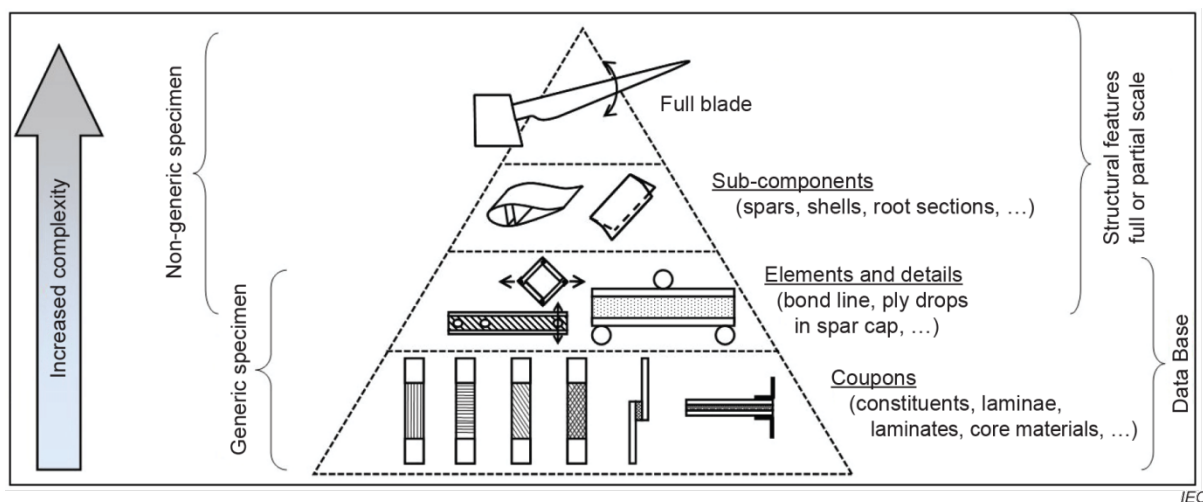


Figure 3 – The building block approach

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.

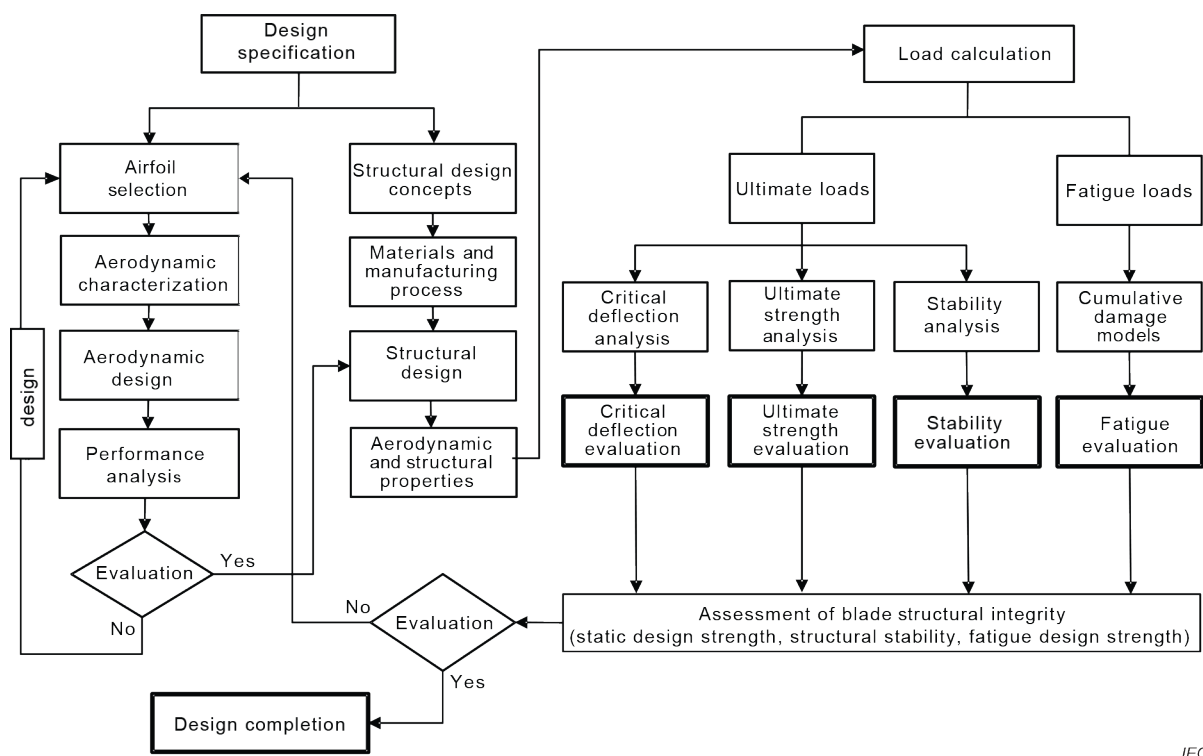
For design values (strength, stiffness, etc.) developed from test at any building block level (material sample, sub-component, etc.), the validity of such design values shall be described and limited by acceptance criteria¹ and tolerances to be met in the final design.

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.

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.



IEC

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:

$$S(\gamma_f \times F_k) \leq \frac{R_k}{\gamma_m \gamma_n}$$

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.

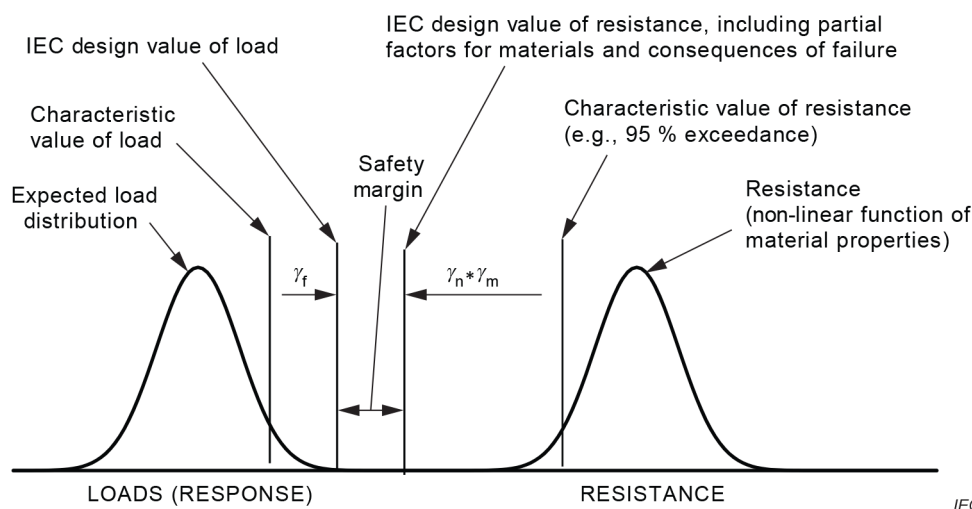


Figure 5 – Application of limit states design approach for blade verification

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 $2,0 \times$ 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.

- profile²
 - shape of the profile $\pm 0,2 \% \times \text{chord}$
 - roughness of the profile surface³ $R_z \leq 15 \mu\text{m}$
 - local chord length (for the inboard 80% of span) $\pm 1,0 \% \times \text{chord}$
- twist angle distribution $\pm 0,2^\circ$
- blade length $\pm 0,1 \% \times \text{length}$
- setup of 0° marking $\pm 0,2^\circ$
- blade mass $\pm 3,0 \%$
- blade static moment $\pm 4,5 \%$
- blade static moment, difference in one set $\pm 0,2 \%$
- blade natural frequency $\pm 5,0 \%$

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.

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:

$$F_d = \gamma_f F_k$$

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. $\gamma_f = 1,0$).

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.

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

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 $1 \times$ 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 $2,0 \times$ 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

- 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:

$$\gamma_m = \gamma_{m0} \gamma_{m1} \gamma_{m2} \gamma_{m3} \gamma_{m4} \gamma_{m5}$$

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 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 mean 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.