BS EN IEC 61400-5:2020+A1:2025



BSI Standards Publication

Wind energy generation systems

Part 5: Wind turbine blades

Documents
Document Sharing Hub

Full document details: BS EN IEC 61400-5:2020+A1:2025

National foreword

This British Standard is the UK implementation of EN IEC 61400-5:2020+A1:2025. It is identical to IEC 61400-5:2020, incorporating amendment 1:2025. It supersedes BS EN IEC 61400-5:2020, which will be withdrawn on 31 October 2028.

The start and finish of text introduced or altered by amendment is indicated in the text by tags. Tags indicating changes to IEC text carry the number of the IEC amendment. For example, text altered by IEC amendment 1 is indicated by A1 A1.

The UK participation in its preparation was entrusted to Technical Committee PEL/88, Wind turbines.

A list of organizations represented on this committee can be obtained on request to its committee manager.

Contractual and legal considerations

This publication has been prepared in good faith, however no representation, warranty, assurance or undertaking (express or implied) is or will be made, and no responsibility or liability is or will be accepted by BSI in relation to the adequacy, accuracy, completeness or reasonableness of this publication. All and any such responsibility and liability is expressly disclaimed to the full extent permitted by the law.

This publication is provided as is, and is to be used at the recipient's own risk.

The recipient is advised to consider seeking professional guidance with respect to its use of this publication.

This publication is not intended to constitute a contract. Users are responsible for its correct application.

© The British Standards Institution 2025
Published by BSI Standards Limited 2025

ISBN 978 0 539 31364 2

ICS 27.180

Compliance with a British Standard cannot confer immunity from legal obligations.

This British Standard was published under the authority of the Standards Policy and Strategy Committee on 31 August 2020.

Amendments/corrigenda issued since publication

Date	Text affected
31 October 2025	Implementation of IEC amendment 1:2025 with CENELEC endorsement A1:2025

Documents
Document Sharing Hub

Full document details: BS EN IEC 61400-5:2020+A1:2025

EUROPEAN STANDARD

NORME EUROPÉENNE

EUROPÄISCHE NORM

EN IEC 61400-5:2020+A1

October 2025

ICS 27.180

English Version

Wind energy generation systems - Part 5: Wind turbine blades (IEC 61400-5:2020)

Systèmes de génération d'énergie éolienne - Partie 5: Pales d'éoliennes (IEC 61400-5:2020)

Windenergieanlagen - Teil 5: Rotorblätter von Windenergieanlagen (IEC 61400-5:2020)

This European Standard was approved by CENELEC on 2020-07-21. CENELEC members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration.

Up-to-date lists and bibliographical references concerning such national standards may be obtained on application to the CEN-CENELEC Management Centre or to any CENELEC member.

This European Standard exists in three official versions (English, French, German). A version in any other language made by translation under the responsibility of a CENELEC member into its own language and notified to the CEN-CENELEC Management Centre has the same status as the official versions.

CENELEC members are the national electrotechnical committees of Austria, Belgium, Bulgaria, Croatia, Cyprus, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Norway, Poland, Portugal, Republic of North Macedonia, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey and the United Kingdom.



European Committee for Electrotechnical Standardization
Comité Européen de Normalisation Electrotechnique
Europäisches Komitee für Elektrotechnische Normung

CEN-CENELEC Management Centre: Rue de la Science 23, B-1040 Brussels

© 2020 CENELEC All rights of exploitation in any form and by any means reserved worldwide for CENELEC Members.

Ref. No. EN IEC 61400-5:2020 E

Documents
Document Sharing Hub

Full document details: BS EN IEC 61400-5:2020+A1:2025

European foreword

The text of document 88/759/FDIS, future edition 1 of IEC 61400-5, prepared by IEC/TC 88 "Wind energy generation systems" was submitted to the IEC-CENELEC parallel vote and approved by CENELEC as EN IEC 61400-5:2020.

The following dates are fixed:

- latest date by which the document has to be implemented at national level by publication of an identical national standard or by endorsement
- latest date by which the national standards conflicting with the document have to be withdrawn

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CENELEC shall not be held responsible for identifying any or all such patent rights.

Endorsement notice

The text of the International Standard IEC 61400-5:2020 was approved by CENELEC as a European Standard without any modification.

European foreword to amendment A1

The text of document 88/1086/FDIS, future edition 1 of IEC 61400-5/AMD1, prepared by TC 88 "Wind energy generation systems" was submitted to the IEC-CENELEC parallel vote and approved by CENELEC as EN IEC 61400-5:2020/A1:2025.

The following dates are fixed:

- latest date by which the document has to be implemented at national level by publication of an identical national standard or by endorsement (dop) 2026-10-31
- latest date by which the national standards conflicting with the document have to be withdrawn (dow) 2028-10-31

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CENELEC shall not be held responsible for identifying any or all such patent rights.

Any feedback and questions on this document should be directed to the users' national committee. A complete listing of these bodies can be found on the CENELEC website.

Endorsement notice

The text of the International Standard IEC 61400-5:2020/AMD1:2025 was approved by CENELEC as a European Standard without any modification.

AVA Documents
Document Sharing Hub

Full document details: BS EN IEC 61400-5:2020+A1:2025

Annex ZA
(normative)

Normative references to international publications with their corresponding European publications

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.

NOTE 1 Where an International Publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

NOTE 2 Up-to-date information on the latest versions of the European Standards listed in this annex is available here: www.cenelec.eu.

Publication	Year	Title	EN/HD	Year
IEC 60050-415	-	International Electrotechnical Vocabulary - Part 415: Wind turbine generator systems	-	-
IEC 61400-1	-	Wind energy generation systems - Part 1: Design requirements	EN IEC 61400-1	-
IEC 61400-2	-	Wind turbines - Part 2: Small wind turbines	EN 61400-2	-
IEC 61400-3-1	-	Wind energy generation systems - Part 3-1: Design requirements for fixed offshore wind turbines	EN IEC 61400-3-1	-
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	EN 61400-23	-
IEC 61400-24	-	Wind energy generation systems - Part 24: Lightning protection	EN IEC 61400-24	-

〖A1〗 *Text deleted* 〖A1〗

ISO 10474	-	Steel and steel products - Inspection documents	-	-
ISO 2394	-	General principles on reliability for structures	-	-
ISO 9000	-	Quality management systems - Fundamentals and vocabulary	EN ISO 9000	-

AVA Documents
Document Sharing Hub

Full document details: BS EN IEC 61400-5:2020+A1:2025

ISO 9001	-	Quality management systems - Requirements	EN ISO 9001	-
-	-	Metallic products - Types of inspection documents	EN 10204	-
ISO 16269-6	-	Statistical interpretation of data - Part 6: Determination of statistical tolerance intervals	-	-

Documents
Document Sharing Hub

CONTENTS

FOREWORD 3
INTRODUCTION 5
1 Scope 6
2 Normative references 6
3 Terms and definitions 7
4 Notation 9
4.1 Symbols 9
4.2 Greek symbols 9
4.3 Subscripts 10
4.4 Coordinate systems 10
5 Design environmental conditions 11
6 Design 12
6.1 Structural design process 12
6.1.1 General requirements 12
6.1.2 Building block approach for composite structural design 12
6.1.3 General blade design process 13
6.1.4 Design loads 16
6.2 Blade characteristics 17
6.2.1 Blade properties 17
6.2.2 Functional design tolerances 17
6.3 Aerodynamic design 18
6.3.1 General 18
6.3.2 Aerodynamic characteristics 18
6.3.3 Power performance characterisation (informative) 19
6.3.4 Airfoil noise (informative) 19
6.4 Material requirements 19
6.4.1 General 19
6.4.2 Material properties for blade design 19
6.4.3 Qualification of materials for manufacture 23
6.5 Design for manufacturing 23
6.5.1 General 23
6.5.2 Requirement for manufacturing tolerances 24
6.6 Structural design 25
6.6.1 General design approach 25
6.6.2 Structural analysis 26
6.6.3 Verification requirements 27
6.6.4 Partial safety factors for materials 29
6.6.5 Structural design verification 32
6.6.6 Additional failure modes 47
7 Manufacturing requirements 48
7.1 Manufacturing process 48
7.2 Workshop requirements 48
7.2.1 General 48
7.2.2 Workshop facilities 49
7.2.3 Material handling and storage facilities 49
7.2.4 Tools and equipment 50

AVA Documents
Document Sharing Hub

Full document details: BS EN IEC 61400-5:2020+A1:2025

7.2.5 Personnel 51
7.3 Quality management system requirements 51
7.4 Manufacturing process requirements 52
7.4.1 General manufacturing requirements 52
7.4.2 Gelcoat application to the mould 52
7.4.3 Building up the laminate 52
7.4.4 Adhesive bonding process 53
7.4.5 Curing 54
7.4.6 Demoulding 55
7.4.7 Trimming, cutting, and grinding 55
7.4.8 Surface finish 55
7.4.9 Sealing 56
7.4.10 Additional component assembly processes 56
7.4.11 Mass and balance 56
7.4.12 Manufacturing and assembly processes outside controlled environment 56
7.5 Manufacture of natural fiber-reinforced rotor blades 57
7.6 Other manufacturing processes 57
7.7 Quality control process 57
7.7.1 Manufacturing quality plan 57
7.7.2 Incoming inspection 57
7.7.3 Manufacturing and quality control records 58
7.7.4 Non-conformity process 59
7.7.5 In manufacture corrective action processes 59
7.7.6 Final manufacturing inspection and conformity review 59
7.7.7 Documentation 60
7.8 Requirements for manufacturing evaluation 61
8 Blade Installation, operation and maintenance 61
8.1 General 61
8.2 Transportation, handling and installation 61
8.3 Maintenance 62
8.3.1 General 62
8.3.2 Scheduled inspections 62

Figure 1 – Chordwise (flatwise, edgewise) coordinate system 10
Figure 2 – Rotor (flapwise, lead-lag) coordinate system 11
Figure 3 – The building block approach 12
Figure 4 – Typical process for design and analytical evaluation of blade 14
Figure 5 – Application of limit states design approach for blade verification 15
Figure 6 – Examples of Independent and non-independent linear buckling modes 40

Table 1 – Typical manufacturing effects 31

Documents
Document Sharing Hub
Full document details: BS EN IEC 61400-5:2020+A1:2025

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.
2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.
3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.
4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.
5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.
6) All users should ensure that they have the latest edition of this publication.
7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.
8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.
9) IEC draws attention to the possibility that the implementation of this document may involve the use of (a) patent(s). IEC takes no position concerning the evidence, validity or applicability of any claimed patent rights in respect thereof. As of the date of publication of this document, IEC had not received notice of (a) patent(s), which may be required to implement this document. However, implementers are cautioned that this may not represent the latest information, which may be obtained from the patent database available at https://patents.iec.ch. IEC shall not be held responsible for identifying any or all such patent rights.

Documents
Document Sharing Hub

Full document details: BS EN IEC 61400-5:2020+A1:2025

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.

Documents
Document Sharing Hub
Full document details: BS EN IEC 61400-5:2020+A1:2025

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.

Documents
Document Sharing Hub
Full document details: BS EN IEC 61400-5:2020+A1:2025

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.

〚A1〛The purpose of this document is to provide a technical reference for designers, manufacturers, purchasers, operators, third party organizations and material suppliers.〚A1〛

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*

Documents
Document Sharing Hub
Full document details: BS EN IEC 61400-5:2020+A1:2025

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*

〖A1〗 *Text deleted* 〖A1〗

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)

〖A1〗 Note 1 to entry: See 61400-1. 〖A1〗

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

Documents
Document Sharing Hub
Full document details: BS EN IEC 61400-5:2020+A1:2025

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

Documents
Document Sharing Hub
Full document details: BS EN IEC 61400-5:2020+A1:2025

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

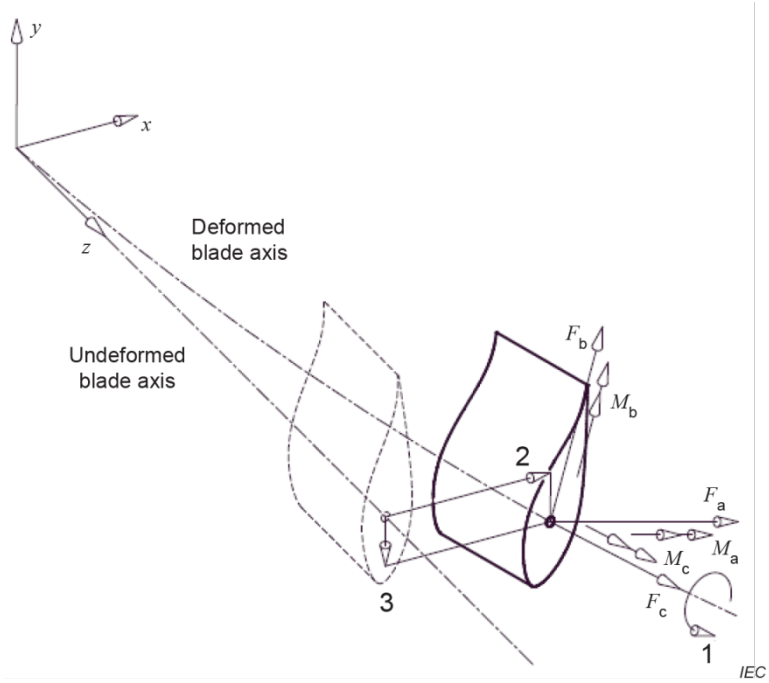
Documents
Document Sharing Hub
Full document details: BS EN IEC 61400-5:2020+A1:2025

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.



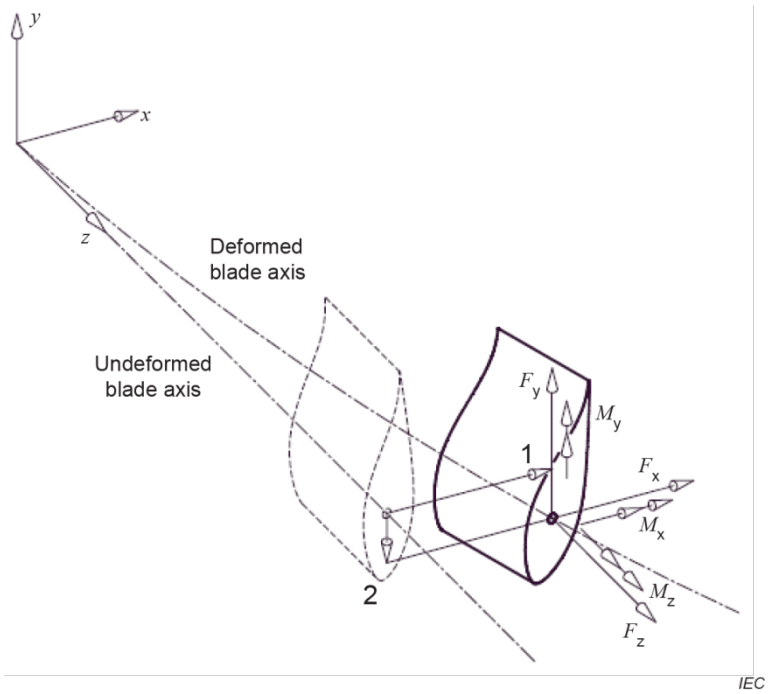
Loads are along and perpendicular to the local blade chord directions.

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

Documents
Document Sharing Hub
Full document details: BS EN IEC 61400-5:2020+A1:2025



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.

Documents
Document Sharing Hub
Full document details: BS EN IEC 61400-5:2020+A1:2025

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.

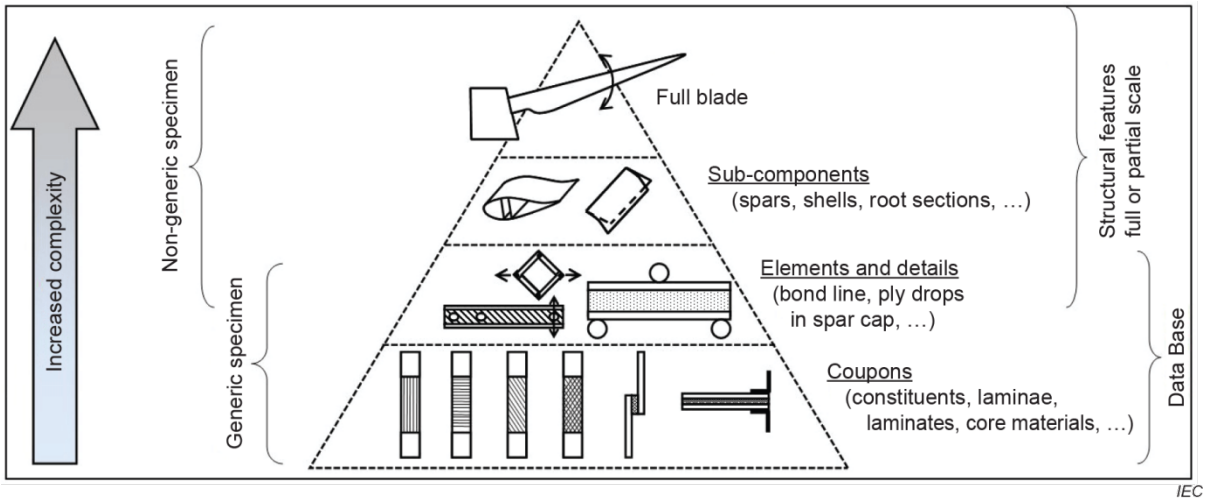


Figure 3 – The building block approach

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.

Documents
Document Sharing Hub
Full document details: BS EN IEC 61400-5:2020+A1:2025

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.

[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.

Documents
Document Sharing Hub
Full document details: BS EN IEC 61400-5:2020+A1:2025

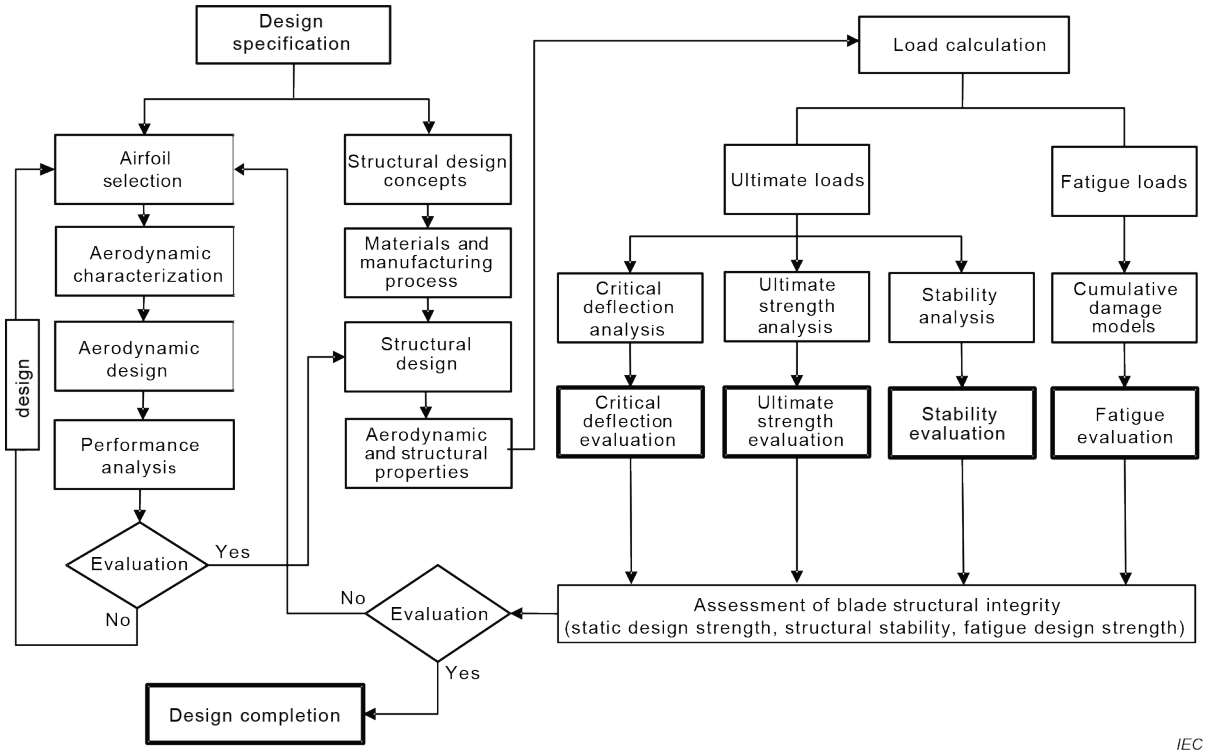


Figure 4 – Typical process for design and analytical evaluation of blade

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.

AVA Documents Document Sharing Hub
Full document details: BS EN IEC 61400-5:2020+A1:2025

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.

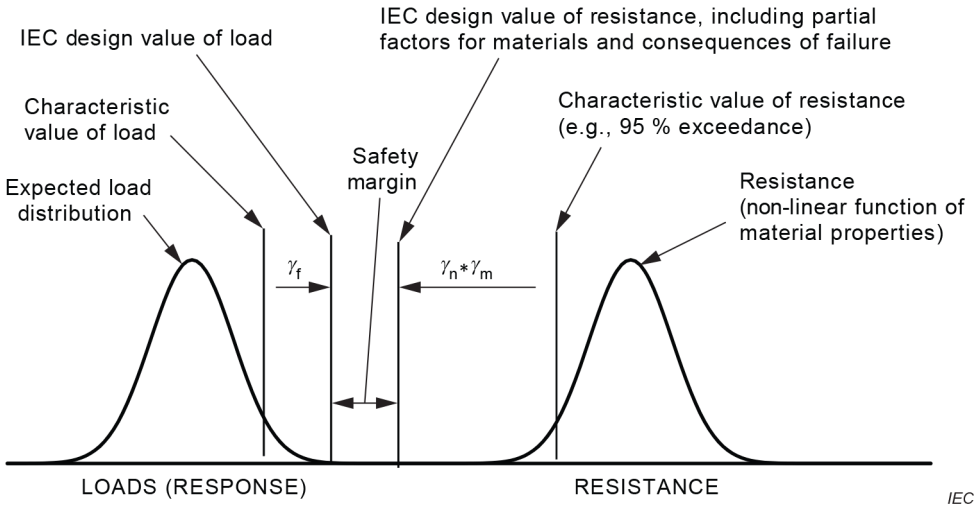


Figure 5 – Application of limit states design approach for blade verification

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.

Documents
Document Sharing Hub
Full document details: BS EN IEC 61400-5:2020+A1:2025