IEC 61400-23

Edition 1.0 2014-04

INTERNATIONAL STANDARD

colour inside

Wind turbines –
Part 23: Full-scale structural testing of rotor blades

IEC 61400-23:2014-04(en)

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

Tel.: +41 22 919 02 11
Fax: +41 22 919 03 00
info@iec.ch
www.iec.ch

About the IEC
The International Electrotechnical Commission (IEC) is the leading global organization that prepares and publishes International Standards for all electrical, electronic and related technologies.

About IEC publications
The technical content of IEC publications is kept under constant review by the IEC. Please make sure that you have the latest edition, a corrigenda or an amendment might have been published.

IEC Catalogue - webstore.iec.ch/catalogue
The stand-alone application for consulting the entire bibliographical information on IEC International Standards, Technical Specifications, Technical Reports and other documents. Available for PC, Mac OS, Android Tablets and iPad.

IEC publications search - www.iec.ch/searchpub
The advanced search enables to find IEC publications by a variety of criteria (reference number, text, technical committee,…). It also gives information on projects, replaced and withdrawn publications.

IEC Just Published - webstore.iec.ch/justpublished
Stay up to date on all new IEC publications. Just Published details all new publications released. Available online and also once a month by email.

Electropedia - www.electropedia.org
The world's leading online dictionary of electronic and electrical terms containing more than 30 000 terms and definitions in English and French, with equivalent terms in 14 additional languages. Also known as the International Electrotechnical Vocabulary (IEV) online.

IEC Glossary - std.iec.ch/glossary
More than 55 000 electrotechnical terminology entries in English and French extracted from the Terms and Definitions clause of IEC publications issued since 2002. Some entries have been collected from earlier publications of IEC TC 37, 77, 86 and CISPR.

IEC Customer Service Centre - webstore.iec.ch/csc
If you wish to give us your feedback on this publication or need further assistance, please contact the Customer Service Centre: csc@iec.ch.

IEC 61400-23

Edition 1.0 2014-04

INTERNATIONAL STANDARD

colour inside

Wind turbines –
Part 23: Full-scale structural testing of rotor blades

INTERNATIONAL ELECTROTECHNICAL COMMISSION

PRICE CODE X

ICS 27.180

ISBN 978-2-8322-1506-7

Warning! Make sure that you obtained this publication from an authorized distributor.

CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

____

WIND TURBINES –

Part 23: Full-scale structural testing of rotor 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) Attention is drawn to the possibility that some of the elements of this IEC Publication may be the subject of patent rights. IEC shall not be held responsible for identifying any or all such patent rights.

International Standard IEC 61400-23 has been prepared by IEC technical committee 88: Wind turbines.

This first edition cancels and replaces IEC TS 61400-23, published in 2001. It constitutes a technical revision.

This edition includes the following significant technical changes with respect to IEC TS 61400-23:

a) description of load based testing only;
b) condensation to describe the general principles and demands.

The text of this standard is based on the following documents:

CDV	Report on voting
88/420/CDV	88/448/RVC

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

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

A list of all parts in the IEC 61400 series, published under the general title *Wind turbines*, can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

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 standard, the demands for full-scale structural testing related to certification are defined as well as the interpretation and evaluation of test results.

Specific testing methods or set-ups for testing are not demanded or included as full-scale blade testing methods historically have developed independently in different countries and laboratories.

Furthermore, demands for tests determining blade properties are included in this standard in order to validate some vital design assumptions used as inputs for the design load calculations.

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

The standard is based on IEC TS 61400-23 published in 2001. Compared to the TS, this standard only describes load based testing and is condensed to describe the general principles and demands.

WIND TURBINES –

Part 23: Full-scale structural testing of rotor blades

1 Scope

This part of IEC 61400 defines the requirements for full-scale structural testing of wind turbine blades and for the interpretation and evaluation of achieved test results. The standard focuses on aspects of testing related to an evaluation of the integrity of the blade, for use by manufacturers and third party investigators.

The following tests are considered in this standard:

- static load tests;
- fatigue tests;
- static load tests after fatigue tests;
- tests determining other blade properties.

The purpose of the tests is to confirm to an acceptable level of probability that the whole population of a blade type fulfils the design assumptions.

It is assumed that the data required to define the parameters of the tests are available and based on the standard for design requirements for wind turbines such as IEC 61400-1 or equivalent. Design loads and blade material data are considered starting points for establishing and evaluating the test loads. The evaluation of the design loads with respect to the actual loads on the wind turbines is outside the scope of this standard.

At the time this standard was written, full-scale tests were carried out on blades of horizontal axis wind turbines. The blades were mostly made of fibre reinforced plastics and wood/epoxy. However, most principles would be applicable to any wind turbine configuration, size and material.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60050-415:1999, *International Electrotechnical Vocabulary – Part 415: Wind turbine generator systems*

IEC 61400-1:2005, *Wind turbines – Part 1: Design requirements*

ISO/IEC 17025:2005, *General requirements for the competence of testing and calibration laboratories*

ISO 2394:1998, *General principles on reliability for structures*

3 Terms and definitions

For the purposes of this document, the terms and definitions related to wind turbines or wind energy given in IEC 60050-415 and the following apply.

3.1
actuator
device that can be controlled to apply a constant or varying force and displacement

3.2
blade root
that part of the rotor blade that is connected to the hub of the rotor

3.3
blade subsystem
integrated set of items that accomplishes a defined objective or function within the blade (e.g., lightning protection subsystem, aerodynamic braking subsystem, monitoring subsystem, aerodynamic control subsystem, etc.)

3.4
buckling
instability characterized by a non-linear increase in out of plane deflection with a change in local compressive load

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
constant amplitude loading
during a fatigue test, the application of load cycles with a constant amplitude and mean value

3.7
creep
time-dependant increase in strain under a sustained load

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

3.9
edgewise
direction that is parallel to the local chord

SEE: 4.4.

3.10
elastic axis
the line, lengthwise of the blade, along which transverse loads are applied in order to produce bending only, with no torsion at any section

Note 1 to entry: Strictly speaking, no such line exists except for a few conditions of loading. Usually the elastic axis is assumed to be the line that passes through the elastic center of every section. This definition is not applicable for blades with bend-twist coupling.

3.11
fatigue formulation
methodology by which the fatigue life is estimated

3.12
fatigue test
test in which a cyclic load of constant or varying amplitude is applied to the test specimen

3.13
fixture
component or device to introduce loads or to support the test specimen

3.14
flapwise
direction that is perpendicular to the surface swept by the undeformed rotor blade axis

SEE: 4.4.

3.15
flatwise
direction that is perpendicular to the local chord, and spanwise blade axis

SEE: 4.4.

3.16
full-scale test
test carried out on the actual blade or part thereof

3.17
inboard
towards the blade root

3.18
lead-lag
direction that is parallel to the plane of the swept surface and perpendicular to the longitudinal axis of the undeformed rotor blade

SEE 4.4.

3.19
load envelope
collection of maximum design loads in all directions and spanwise positions

3.20
natural frequency
eigen frequency
frequency at which a structure will vibrate when perturbed and allowed to vibrate freely

3.21
partial safety factors
factors that are applied to loads and material strengths to account for uncertainties in the representative (characteristic) values

3.22
prebend
blade curvature in the flapwise plane in the unloaded condition

3.23
R-value
ratio between minimum and maximum value during a load cycle

3.24
S-N formulation
method used to describe the stress and/or strain (S) vs. cycle (N) characteristics of a material, component or structure

3.25
spanwise
direction parallel to the longitudinal axis of a rotor blade

3.26
static test
test with an application of a single load cycle without introducing dynamic effects

3.27
stiffness
ratio of change of force to the corresponding change in displacement of an elastic body

3.28
strain
ratio of the elongation (or shear displacement) of a material subjected to stress to the original length of the material

3.29
sweep
blade curvature in the lead-lag plane in the unloaded condition

3.30
tare loads
gravitational or other loads that are inherent to the test set-up

3.31
target load
load that is developed from the design load and is the ideal test load

3.32
test load
forces applied during a test

3.33
tested area
region of the test object that experiences the intended loading

3.34
twist
spanwise variation in angle of the chord lines of blade cross-sections

3.35
variable amplitude loading
application of load cycles of non-constant mean and/or cyclic range

3.36
whiffle tree
device for distributing a single load source over multiple points on a test specimen

4 Notation

4.1 Symbols

C	conversion factors for material strength
D	theoretical damage
F	load
F_{a}	flatwise shear force (chordwise co-ordinates)
F_{b}	edgewise shear force (chordwise co-ordinates)
F_{c}	spanwise (tensile) force (chordwise co-ordinates)
F_{x}	flapwise shear force (rotor co-ordinate system)
F_{y}	lead-lag shear force (rotor co-ordinate system)
F_{z}	spanwise (tensile) force (rotor co-ordinate system)
M_{a}	edgewise bending moment (chordwise co-ordinates)
M_{b}	flatwise bending moment (chordwise co-ordinates)
M_{c}	blade torsion moment (chordwise co-ordinates)
M_{x}	lead-lag bending moment (rotor co-ordinate system)
M_{y}	flapwise bending moment (rotor co-ordinate system)
M_{z}	blade torsion moment (rotor co-ordinate system)
N	cycle
S	strain or stress

4.2 Greek symbols

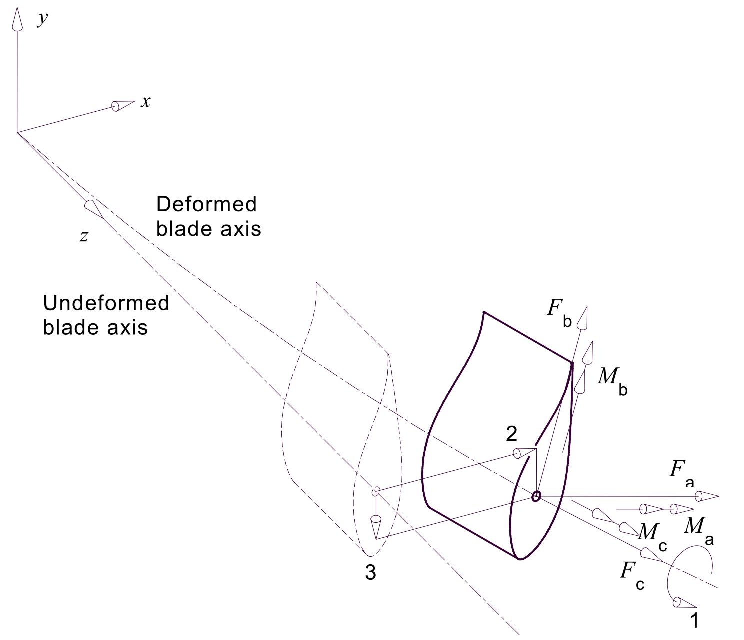
γ	partial factor or test load factor
σ	applied stress or strain

4.3 Subscripts

design	design loading conditions
df	design load: fatigue
du	design load: static
ef	uncertainty in fatigue formulation of test load
f	load
lf	environmental effects: fatigue
lu	environmental effects: static
m	material
n	consequence of failure
nf	consequence of failure: fatigue
nu	consequence of failure: static
sf	blade to blade variation: fatigue test load
su	blade to blade variation: static test load
target	target loading conditions
test	test loading conditions

4.4 Coordinate systems

Two different coordinate systems may be used for reference during structural testing. The first, shown in Figure 1, references the local blade chord directions. The second, shown in Figure 2, references the global rotor plane directions.

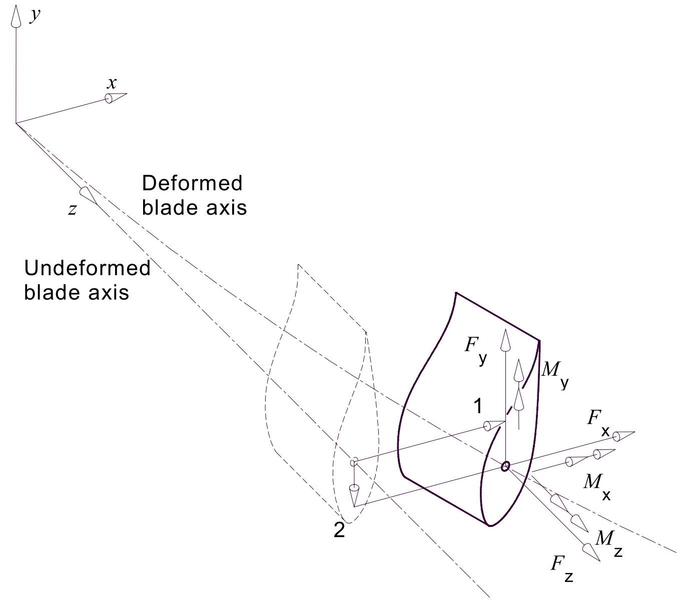


Loads are along and perpendicular to the local blade chord directions

- 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

IEC 1040/14

Figure 1 – Chordwise (flatwise, edgewise) coordinate system



Loads are along the rotor plane reference directions

- 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

IEC 1041/14

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

5 General principles

5.1 Purpose of tests

The fundamental purpose of a wind turbine blade test is to demonstrate to a reasonable level of certainty that a blade type, when manufactured according to a certain set of specifications, has the prescribed reliability with reference to specific limit states, or, more precisely, to verify that the specified limit states are not reached and the blades therefore possess the load carrying capability and service life provided for in the design.

Additionally, tests determining blade properties have to be performed in order to validate some vital design assumptions used as inputs for the design load calculations. It has to be pointed out that the required blade property tests do not cover all design assumptions.

Normally, the full-scale tests dealt within this standard are tests on a limited number of samples; only one or two blades of a given design are tested, so no statistical distribution of production blade load carrying capability can be obtained. Although the tests do give information valid for the blade type, they cannot replace either a rigorous design process or the quality system for series blade production. Furthermore, the tests described in this standard are not intended to be used for the testing of mechanism function nor to establish basic material strength or fatigue design data for blades and/or components.

5.2 Limit states

To establish and evaluate the test load, a certain amount of information about the design shall be known. Usually the blades are designed according to some standard or code of practice such as IEC 61400-1 that uses the principles of ISO 2394 defining the limit states and partial coefficients, which have to be applied to obtain the corresponding design values. A limit state is a state of the structure and the loads acting upon it, beyond which the structure no longer satisfies the design requirements. The partial coefficients reflect uncertainties and are chosen – at least in principle – in order to keep the probability of a limit state being reached below a certain value prescribed for the structure. According to this, a blade should pass the test if the limit state is not reached when the blade is exposed to the test load, representative of the design load.

The basis for establishing the test loads is the entire envelope of blade design loads, derived according to IEC 61400-1 or equivalent. The representative test load can be higher than the design load to account for other influences, for example, environmental effects, test uncertainties, and variations in production (see Clause 8).

The determination of the actual margins to the limit states might be desirable because such margins can provide a measure of the actual safety obtained for the resistance of the test blade. However, interpretation of such values is not straightforward and probabilistic methods have to be applied. In this standard, only the ultimate limit state and fatigue are dealt with.

5.3 Practical constraints

The practical execution of the tests is subject to many constraints of a technical and economic character. Some of the most important are listed below:

- the distributed load on the blade can be simulated only approximately;
- the time available for testing is generally one year or less;
- only one or a few blades can be tested;
- certain failures are difficult to detect.

The test will be a compromise because these constraints have to be dealt with in such a way that the final test results can be used for evaluation of the defined limit states.

As regards the interpretation of the results, it should be borne in mind that the blade used for testing will normally be one of the first blades from series production which will be subject to evolutionary modifications. Even minor modifications could compromise the validity of the tests (see Annex A).

5.4 Results of test

The design loads form the basis of the test loading. According to the design calculation, the blade shall be able to survive the design loading. In these design calculations, a number of assumptions are implicitly being made:

- the stresses or strains are calculated accurately or conservatively estimated;
- the classifications of strength and fatigue resistance of all relevant materials and details are estimated accurately or conservatively;
- the strength and fatigue formulations used to calculate the strength are accurate or conservative;
- the production is according to the design.

In a full-scale test used as final design verification, the validity of the assumptions mentioned above are checked simultaneously. When a blade fails during testing, at least one of these assumptions has been violated, although without further analysis it might not be clear what caused this unexpected failure.

If no damage to the blade has occurred during the test and the blade structure and the test loading has been evaluated correctly, this gives a strong indication that the blade design will fulfil its requirements. It should be noted that the blade property tests make it possible to check some of the main design assumptions used for the design calculations.

6 Documentation and procedures for test blade

The blade manufacturer shall record traceable documentary evidence for the design and construction of the test blade. The records should cover:

- unique identification;
- relevant drawings and specifications;
- lamination plans and work instructions;
- listing of manufacturer, type and identification number for all important materials used;
- supplier's certificate and blade manufactures laboratory acceptance report for all important materials used;
- curing history thermographs for thermosetting resins and adhesives at critical locations;
- differential scanning calorimetry or other control of curing;
- manufacturing quality record sheets signed by responsible person;
- weight and balance report detailing total mass and centre of gravity. This report shall include information about any loose items fitted during weighing e.g., root joint elements and damper fluids;
- relevant reports on manufacturing deviations.

Repairs shall also be documented. The records should cover the above list. Repairs may be:

- representative examples for repair procedures for manufacturing defects and in-service damage that are qualified with the test blade;
- repairs performed due to damage caused by test loads higher than the target loads (see 9.3 and 9.4).

Special blade modifications can be present for test purposes. During the fatigue tests the loads may have to be magnified to complete the test within an acceptable time-frame. In some cases, the required magnification of the fatigue loads may lead to failure of areas not considered to be tested. In these cases, special blade modifications can be considered. Modification might also be due to load introduction reinforcements. All special blade modifications shall be documented.

7 Blade test program and test plans

7.1 Areas to be tested

No single test can load the whole blade optimally. All critical areas should be loaded at a minimum to the target loads. These areas are discussed in Annex B. Lead-lag and flap tests may be sufficient – but that shall be evaluated (see Annex D).

7.2 Test program

The test program for a blade type shall be composed of at least the following tests in this order:

- mass, centre of gravity and natural frequencies (see 10.4.1 and 10.4.2);
- static tests (see 9.3 and 10.2);
- fatigue load tests (see 9.4 and 10.3);
- post fatigue static tests.

Testing of other blade properties could be of interest (see 10.4.3).

All tests in a given direction and in a given area of a blade shall be performed on the same blade part. The flap and lead-lag sequence of testing may be performed on two separate blades. However, if an area of the blade is critical due to the combination of flap and lead-lag loading, then the entire test sequence shall be performed on one blade.

The test program shall include blade inspection (see Clause 11).

7.3 Test plans

7.3.1 General

Test plans shall be established for all the individual tests in the blade test program. The test plans shall include a blade description, specification of loads, conditions and the instrumentation to be applied in the test.

7.3.2 Blade description

The blade description in the test plan shall be sufficient to ensure that the blade will fit the test stand and avoid unintended overloading during storage, handling, lifting, mounting and testing in the laboratory.

The following information shall be supplied:

- blade geometry (preferably in form of a drawing):
  - blade length;
  - chord and twist distribution;
  - pre-bend or sweep;
- mass and center of gravity;
- blade surface condition;
- blade mounting details:
  - bolt pattern (including tolerances) and interface dimension;
  - bolt size, type and grade;
  - bolt clamping length;
  - bolt pretension or torque procedure;

- lifting and handling procedures;
- maximum expected deflections under load;
- profile geometry at load introduction points.

Additional information (such as mounting structure stiffness) may be required depending on the test specifics.

7.3.3 Loads and conditions

The test plan shall include the target loads, test loads, application methods and sequence of the tests to be conducted. Environmental conditions that may affect the execution of the tests shall also be given in the test plan (see 8.3.3).

7.3.4 Instrumentation

The position and orientation of load cells, strain gauges, deflection transducers and other sensors shall be specified in the test plan.

7.3.5 Expected test results

It is recommended that predictions (deflections, strains, etc.) are provided corresponding to all sensor measurements to enable and assist planning, evaluation and quality control.

8 Load factors for testing

8.1 General

In testing, various load factors have to be taken into account. Those arising from the design are discussed in 8.2. Apart from these, additional test load factors have to be applied to account for effects introduced by the test methodology. These test load factors are discussed in 8.3.

8.2 Partial safety factors used in the design

8.2.1 General

In the design calculations, partial safety factors (or coefficients) have to be included. According to IEC 61400-1, these include:

γ_m: partial material factors;

γ_n: partial factors for consequences of failure;

γ_f: partial load factors.

In the design calculation, all three partial safety factors (γ_m, γ_n and γ_f) have to be applied. The product of these partial factors is an important figure for the overall safety level of the design. For the test load, only γ_f and γ_n will affect the test load for reasons given in the following subclauses.

8.2.2 Partial factors on materials

Material data are normally based on tests of coupons produced and tested under laboratory conditions.

Material conversion factors take into account specific differences between the conditions of the material in the structure and the conditions for which the strength and fatigue formulation were derived. Examples of these conversion factors are factors for size effects, humidity, aging and temperature. These will be applied implicitly using the appropriate strength and fatigue formulation during the evaluation.

The partial factor for materials, γ_m, is applied in the design to account for uncertainties in the conversion factors and the possibility of unfavorable deviations of the material properties from the characteristic values. The test loads should not be increased by this partial factor (γ_m) because the material in the blade being tested is the actual material.

8.2.3 Partial factors for consequences of failure

The partial factors for consequences of failure, γ_n, according to IEC 61400-1, are factors by which the importance of the structure and the consequences of failure, including the significance of the type of failure, are taken into account.[1] The reason is that for a non-fail-safe component (such as a blade) a higher level of safety against failure is required than for a fail-safe component. In this case, the full-scale test shall reflect this additional safety requirement. As a consequence, these factors shall be included in the test load.

8.2.4 Partial factors on loads

During the design, the partial factors on loads γ_f take into account the uncertainties in the loads. Therefore, the test blade shall be able to resist the design load (which includes the appropriate partial factors for loads).

8.3 Test load factors

8.3.1 Blade to blade variation

If there is no failure probability distribution data available for the particular blade design and particular manufacturing procedure, the following test load factors shall be used:

for static tests: $\gamma_{su} = 1,1$

for fatigue tests: $\gamma_{sf} = 1,1$

The static load factor above shall be used for at least one of the two required static tests (pre or post fatigue). For the other static test, γ_{su} can be set to 1,0.

8.3.2 Possible errors in the fatigue formulation

Due to the conversion of the original fatigue design loads to fatigue test loads, an uncertainty is introduced due to possible errors in the fatigue formulation.

The more the fatigue test is accelerated, i.e. the lower the number of cycles in the fatigue test, the larger the uncertainty connected to the conversion from the fatigue design loads to the fatigue test loads.

For fatigue tests, this shall be accounted for by applying the factor γ_{ef} to the fatigue test loads. The value of γ_{ef} is given for different numbers of test load cycles in the Table 1 below (see Annex F).

Table 1 – Recommended values for γ_{ef} for different number of load cycles

Number of load cycles	γ_{ef}
5×10^5	1,065
1×10^6	1,050
$2,5 \times 10^6$	1,035
5×10^6	1,025
1×10^7	1,015

1 In some codes, this is taken into account by applying different partial factors on loads.

For fatigue tests using a number of load cycles different from those given in the table above, γ_{ef} is either conservatively selected or found by interpolation or extrapolation.

8.3.3 Environmental conditions

In general, the conditions at the test facility are more benign than the actual operational and consequently design conditions. In many strength and fatigue formulations, the effect of these conditions is expressed by factors. However, it can also result in different strength or fatigue formulation for the different conditions.

When the test conditions are more benign, this leads to a magnification of the required test load. The appropriate factor has to be checked by the evaluation of the test load distribution, but for both conditions the appropriate strength or fatigue formulation has to be applied (see Annex E). Whenever the effect is given by factors, these can be used as an initial estimate for the factor necessary to magnify the load to arrive at an equivalent test load.

8.4 Application of load factors to obtain the target load

For the tests, the design load is compiled into a target load. The test load should ideally be equivalent to the target load. The determination of the target loads shall be based on appropriate strength and/or fatigue formulations and elastic properties for the materials used in the areas to be tested.

The target load for the static test is defined as:

$$F_{\text{target-u}} = F_{\text{du}} \cdot \gamma_{\text{nu}} \cdot \gamma_{\text{su}} \cdot \gamma_{\text{lu}} \tag{1}$$

where

$F_{\text{target-u}}$ is the target loading;

F_{du} is the design loading (including partial factor for loads γ_f) (see 8.2.1);

γ_{nu} is the partial factor for consequence of failure (see 8.2.3);

γ_{su} is the test load factor for blade to blade variation (see 8.3.1);

γ_{lu} is the test load factor for environmental effects, if applicable (see 8.3.3).

The target load for the fatigue test is defined as:

$$F_{\text{target-f}} = F_{\text{df}} \cdot \gamma_{\text{nf}} \cdot \gamma_{\text{sf}} \cdot \gamma_{\text{ef}} \cdot \gamma_{\text{lf}} \tag{2}$$

where

$F_{\text{target-f}}$ is the target loading;

F_{df} is the damage equivalent design loading (including partial factor for loads γ_f) (see 8.2.1);

γ_{nf} is the partial factor for consequence of failure (see 8.2.3);

γ_{sf} is the test load factor for blade to blade variation (see 8.3.1);

γ_{ef} is the test load factor for errors in the fatigue formulation (see 8.3.2);

γ_{lf} is the test load factor for environmental effects, if applicable. Alternatively the environmental effects can be accounted for in the conversion from design loads to damage equivalent design loads, if applicable (see 8.3.3).

The determination of the damage equivalent design loads for fatigue includes appropriate S-N formulation(s), cycle counting procedures, an appropriate damage summation model, R-value effects, and all other relevant information.

9 Test loading and test load evaluation

9.1 General

For each test, the target loads shall be defined in the test plan. Sufficient information shall be provided to allow the test load to be accurately assessed against the target load. In principle, the six load components should be given, including phase and frequency information required to generate combined load cases. In reality, the load components lead-lag and flapwise moments are the far most important components. Lead-lag and flapwise shear loads will normally implicitly be taken care of because of the moments. Only for more specialized blades will the torsion and lengthwise forces have to be taken into account. The coordinate system relevant for the load components shall be clearly specified (see 4.4). The large deflections of the blade during testing typically lead to changes in load direction with magnitude (see Annex C). Effects of changes in load direction shall be carefully considered when preparing the test plans and reports and when estimating uncertainties according to 10.1.3.

Since the test should prove that the blade can survive the target loading, the test loading shall be evaluated. It should be checked in which areas of the blade the severity of the test loading is indeed equal to or more severe than the target loading. Because the severity of the test loading compared to the target loading will vary over the blade area, in principle the evaluation has to be done at all locations of the blade area that are to be tested. Some examples of test evaluation are presented in Annex D.

Loads on critical mechanical and electrical blade subsystems, such as tip brakes and lightning protection components, are often different in character from the general loads on the blades and may need extra specification and specific tests. In the case of mechanisms, it is unlikely that sufficient loading conditions will be present in the standard tests to qualify the subsystem integrity. Additional testing may be necessary to simulate special case loading, including torsion and radial loading. For systems whose failure may result in unsafe operation of the turbine, special consideration shall be given to verify the appropriate level of structural integrity. The accumulated damage should not cause functional failure of these subsystems. Loads for testing of blade subsystems are not covered further in this standard.

9.2 Influence of load introduction

In the case where the test load is introduced as concentrated forces at a restricted number of locations (e.g. at actuator positions), the sections where the load is applied are disturbed and may be strengthened over a certain area by the load introduction fixtures. Therefore, at these areas the blade may not be properly tested and should not be considered in the analysis or evaluation. The length (in the longitudinal direction) of the disturbed area can be estimated from calculations or measurements.

Without further analysis, it could be assumed that this affected area might extend as much as three quarters of the chord length on either side of the fixture. In saddle design, special attention should be given to buckling sensitive areas (e.g. trailing edge in compression).

Also, if special modifications are made for test purposes (see Clause 6), the above-mentioned considerations are relevant.

9.3 Static load testing

In static load testing, the area to be tested shall be loaded to each of its most severe design load conditions while taking into account the variations in a population of manufactured blades and differences between the laboratory and the design environmental conditions (see 8.3.1 and 8.3.3).

If different load distributions or orientations are needed to represent the different extreme load cases in the areas to be tested, each of these shall be applied. For discussion of load directions, see Clause D.1.

It should be noted that the blade may be most vulnerable to certain failure modes when a resultant load, which is not necessarily the highest in magnitude, is appropriately applied in a particular direction. For each load the blade shall withstand the maximum load for the specified load duration. Since most common blade materials exhibit a reduction of strength with duration of load, the duration of the test load shall be at least as long as the peak design load. If the design load information provides a well-defined duration for the peak load on the blade, the test load and duration shall be based directly on that. If no duration of constant test load is stated, then 10 s shall be the minimum value.

In general all locations will be regarded as sufficiently tested if the loading during the static load test is equal to or higher than the target load. In case of failures caused by loads higher than target loads, repair is allowed before a fatigue test.

If the blade is tested with combined loading, it is not intended to combine maximum load in one direction with maximum load in the other direction. Instead, the maximum load in one direction should be combined with an appropriate load in the other direction.

9.4 Fatigue load testing

On the areas to be tested, a test loading has to be generated giving a fatigue damage equivalent to the fatigue damage caused by the target loads. The fatigue test loads will generally be chosen in such a way that, for practical reasons, the test time is reduced. To test areas around the whole blade cross-section, various combinations of flatwise and edgewise loading may be employed.

To reduce the number of cycles during the test, the load normally has to be increased to obtain a reasonable compromise between testing as realistically as possible and obtaining a more reasonable testing time.

The magnification shall lead to the appropriate theoretical equivalent fatigue damage accumulation, having the following limitations in mind:

- the maximum values of the stresses or strains might surpass the static strength of the material and consequently lead to static damage or failure;
- the stresses or strains may be so high that the usual assumption of the linearity between forces and stresses no longer applies, such as in the case of buckling;
- internal heating of the highly stressed areas.

Especially in the case of variable amplitude loading, these limits can be reached at a relatively low load magnification factor. In that case, only the intermediate load cycles can be increased further, and the test loading becomes more and more a constant-amplitude loading as a consequence.

The mean loads applied during fatigue testing shall normally be as close as possible to the mean load at the operating conditions that are most severe to the fatigue strength.

Locations will be regarded as sufficiently tested if the theoretical damage (e.g. Miner summation) during the fatigue test is equal to or higher than the theoretical damage based on the target load.

The theoretical test damage can be evaluated by accumulation of the damage from all partial tests.

When a certain area of the blade fails after it has been subjected to theoretical damage due to the test load that is equivalent to or higher than the damage due to the target load, that area has passed the test. In principle, testing of the blade can continue to reach equal severity for the other areas. This is only valid for the areas that are not affected by stress redistribution due to the damage.

In case of failures caused by loads higher than target loads, repair is allowed. The consequences of any repairs shall be evaluated.

10 Test requirements

10.1 General

10.1.1 Test records

All test activities shall be noted in a log book.

10.1.2 Instrumentation calibration

All instrumentation used to collect data for evaluation of test results shall be calibrated. In the case of applied sensors and gauges that cannot be independently calibrated, specifications shall be traceable and the remaining chain shall be calibrated. Procedures for controlling, calibrating, maintaining and inspecting measuring and test equipment shall be developed and implemented in accordance with ISO/IEC 17025 or equivalent. When possible, an end-to-end calibration of the system should be made, verifying performance of all system components. In the procedures, it shall be addressed that recalibration has to be done for sensors that might be damaged as a consequence of a catastrophic blade or equipment failure during testing.[2]

10.1.3 Measurement uncertainties

All device uncertainties shall be listed in the test report.

In addition, the following uncertainties shall be estimated and reported:

- uncertainties in magnitude, direction and location of any applied load;
- uncertainties in magnitude, direction and location of displacement;
- uncertainties in magnitude, direction and location of the measured strain.[3]

10.1.4 Root fixture and test stand requirements

In case the root area and fixture is considered for testing, deviations between the test stand and the wind turbine blade assembly shall be evaluated.

The measured deflection of the blade should be corrected for deformation of the blade root fixture and the test stand. For the measured natural frequencies, damping and mode shapes, the effect of the test stand shall be considered. For relatively rigid test stands (contribution to tip deflection less than 1 %), the effect of the test stand can be ignored.

10.1.5 Environmental conditions monitoring

Environmental records may be necessary to quantify effects on the test blade such as stiffness variations, strain gauge drift (particularly on single element bridges) or drift in other sensors.

---

[2] Failure of the blade or equipment can result in overloading a sensor such as a load cell. Due to the possible strong dynamic effects, this overloading may be present during such a short period that it might not be (fully) detected by the measurement system.

[3] The tolerance of a strain gauge is typically smaller than 1 %. However, strain gauges are often made of materials that are much stiffer than the coatings and adhesives used in wind turbine blade design. This implies that strain gauge design may have an impact on readings where strain gauges are applied on the surface of thick coatings and adhesives. Such readings on the surface of thick coatings and adhesives may not be representative for the strain in laminates below the coating or adhesive. Application of large strain gauges or removal of coating by grinding may reduce the difference between the strain gauge reading and the true strain in the laminates.

As a minimum, the temperature shall be recorded outside and inside the blade and on the blade surface to evaluate the difference between ambient temperature and blade temperature. These records shall be kept at time intervals sufficient to monitor fluctuations during all tests.

For materials influenced by moisture, the ambient humidity shall be recorded at intervals sufficient to monitor fluctuations during the test.

10.1.6 Deterministic corrections

10.1.6.1 Tare loads

The test may be influenced by gravitational loads that are not part of the test load or measured by the instrumentation. These loads shall be properly accounted for during the test and processing of the test data.

Tare loads can result from the masses of

- the blade itself;
- load introduction fixtures (actuators, whiffle tree apparatus, clamping structures, etc.);
- cables, slings, and transducers.

Tare loads and their location with respect to the blade co-ordinate system shall be documented.

10.1.6.2 Load angle changes

As the blade deflects, the load direction relative to the blade orientation can change. These load direction changes shall be taken into account. This is explained further in Annex C.

10.1.6.3 Induced torsion loading

Loads not acting through the elastic axis either due to deflection, pre-bending or test set-up will cause torsion moments in the blade. These moments can be significant and should be considered when specifying the test load. The applied loads may be intentionally offset from the elastic axis to give a prescribed torsion moment.

10.2 Static test

10.2.1 General

Testing using static loads is undertaken to obtain two separate types of information. One set of information relates to the blade’s ability to resist the loads that the blade has been designed for. The second set of information relates to blade properties, strains and deflections arising from the applied loads. For convenience, the two sets of information are usually obtained during the same static test, although this is not a normative requirement.

10.2.2 Static load test

During the static load tests the following shall be measured (or derived from measurement) and recorded:

- magnitude and direction of the applied load(s) at the five load levels where strains are measured (see 10.2.3);
- a time signal – to assure minimal time at a load level (see 9.3). This can be in the form of an actual time signal or can be derived from the sample rate.

10.2.3 Strain measurement

The strains in the rotor blade shall be measured in areas of interest. Strain gauges are the preferred device used for these measurements. Depending on the areas of interest, strains in one or more directions shall be measured. As a minimum the strains at the following areas of interest shall be measured:

- the main load carrying structure (spar cap, beam flange) in the upper and lower shell, at four cross sections distributed over the area to be tested. The direction of strain measurement is typically longitudinal to the blade spanwise axis, but can be in other directions as required by model verification;
- the trailing and leading edges at the position of the maximum chord length and at half the blade length. The direction of strain measurement is typically parallel to the edges of the blade, but can be in other directions as required by model verification;
- the webs at the blade root area and on a web section with high calculated strain. Shear strain is the important strain measurement required and typically strain gauge rosettes are used;
- the two highest loaded connecting bolts, if the bolts are an integral part of the area to be tested. Both bolt tension and bending shall be measured.

Other areas of interest for strain measurements are typically at blade locations in which geometry transitions and critical design details are present, or the strain level is expected to be high.

The location and the orientation of the individual strain measurements shall be accurately documented. Strain measurements shall be taken for at least five load levels, distributed over the load range used in the test.

10.2.4 Deflection measurement

Deflection shall be measured at a number of points adequate to determine the deflection throughout the blade, but at not less than three locations. Flapwise deflections shall be measured in enough locations and at high enough loads to validate design tip deflection calculations.

10.3 Fatigue test

During the fatigue tests the following shall be measured and recorded:

- cycle count;
- signals that are used to control the blade test (for example: applied loads, deflections, acceleration, strains).

The functionality of the sensors shall be verified throughout the test. If a sensor or instrument fails during the fatigue test, its criticality for the test shall be assessed. Those that are critical to the fatigue test shall be fixed or replaced. To prove that the assumptions for the fatigue test are still valid, the stiffness of the blade should be checked and documented several times (e.g. 5) throughout the test.

10.4 Other blade property tests

10.4.1 Blade mass and center of gravity

The blade mass and the spanwise location of the center of gravity shall be determined. Subcomponents included (e.g. root bolts) shall be stated.

10.4.2 Natural frequencies

As a minimum, the first and second flatwise and first edgewise frequencies shall be measured. The mass of the test instrumentation can influence the results of the natural frequency tests.

10.4.3 Optional blade property tests

Testing of other blade properties may be of interest. These may include (but are not limited to):

- damping;
- mode shapes;
- creep;
- mass distribution;
- stiffness distribution.

11 Test results evaluation

11.1 General

Before starting the test program, after each test and at frequent intervals during the fatigue test, the blade shall be visually inspected on both the inside and outside.

Infrared or ultrasonic inspection and recording of sound emission may be used to supplement the visual inspection.

Inspection results shall be documented in the logbook. Observations shall be accompanied by appropriate documentation.

Critical electrical mounted or imbedded systems such as lightning down conductors or control related sensors shall be inspected and checked for proper function periodically throughout the test program.

In Clause 11, irreversible property changes of the blade are considered as damage. The following types of damage are defined:

- damage in form of catastrophic failure of test blade;
- damage in form of permanent deformation, loss of stiffness or change in other blade properties;
- superficial damage.

Observed damage shall be considered by the designer in a failure evaluation (see 11.5).

For detailed investigations after the test, the blade may be sectioned.

11.2 Catastrophic failure

Catastrophic failure is disintegration or collapse of a component or the complete test blade. Catastrophic failure results in loss of vital function which impairs safety. The following observations can be considered as catastrophic failure:

- breaking or collapse of the primary blade structure;
- complete failure of structural elements such as internal or external bond lines, skins, shear webs, root fasteners etc.;
- major parts become separated from the main structure.

Catastrophic failure is normally readily observed.

Observations shall be documented by description in writing and recording in form of photography or video.

11.3 Permanent deformation, loss of stiffness or change in other blade properties

The mass, center of gravity and natural frequencies measured before the static test (see 7.2, 10.4.1 and 10.4.2) shall be evaluated against the design assumptions. Other measured blade properties as described in 10.2.3 and 10.2.4 (strain distribution and deflection) shall be evaluated both after the static test and after the post fatigue static test.

The measurement of loads, deflections, strains and/or natural frequencies according to 10.2.2, 10.2.3, 10.2.4 and 10.4.2 shall be evaluated to detect possible loss of stiffness and/or permanent deformation.

11.4 Superficial damage

Marking of time and extent of damage on the blade surface shall be used for reference when observing progress of damage throughout the test program.

The following examples of observations can be considered as superficial damages:

- small cracks in laminate or bond lines;
- gelcoat cracking;
- paint flaking;
- surface bubbles;
- minor panel buckling without permanent deformation or damage;
- small delaminations.

In case repair of any of the superficial damages is described in the Operation and maintenance manual for the blade type, these damages are allowed to be repaired during the testing. For example, that could be the case for small cracks in laminate or bond lines, gelcoat cracks or paint flaking. If repairs are carried out, they have to be documented according to Clause 6.

11.5 Failure evaluation

Damage in the form of permanent deformation or loss of stiffness can be catastrophic or lead to functional failure for a blade in service.

Superficial damage can develop into functional or catastrophic failure over time in environmental conditions experienced by blades in service.

The designer shall evaluate the damages observed during the initial static tests and the fatigue tests and determine the effect on safety against catastrophic or functional failure. The basis for this evaluation is not covered by the present standard.

12 Reporting

12.1 General

The tests shall be documented in a report containing enough information to make the tests and their results comprehensible.

12.2 Test report content

The test report(s) shall include the following items, depending on the type of test:

- table of contents;
- contractor for the test;
- dates and locations for the tests;
- blade identification;
- blade description;
- test set-up and procedures;
- description of test load;
- test equipment used (including make, model, serial numbers, etc.);
- reference to calibration records of measurement equipment;
- locations of sensors and measurement points;
- blade specific calibration details (tare loads, strains, etc.);
- estimated uncertainties;
- description of inspections, repairs and observations;
- summary of tests and test results;
- deviations from test plans, laboratory procedures or normative references;
- list of references (test plans, laboratory procedures, normative references).

12.3 Evaluation of test in relation to design requirements

The evaluation of the test in relation to the design requirements shall at least include:

- evaluation of test loads including test load distribution;
- evaluation test results with respect to basis for design;
- evaluation of blade stiffness.

Annex A
(informative)

Guidelines for the necessity of renewed static and fatigue testing

Due to adjustments in the production, improvements in designs and optimizations in general, the production rotor blades will often deviate from the blade that was originally used for full-scale testing.

Since it is impractical to repeat the full-scale test every time adjustments and improvements are made, it is necessary to make a distinction between changes requiring or not requiring a renewed full-scale test. While such requirements are outside the scope of this standard, and are left to the judgment of the manufacturer and/or certification body, some considerations are given below.

Observations made from the previous full-scale test should be considered, since these may indicate the correctness of the design assumptions and be valuable in assessing the need for retesting. Given the level of change, needs for renewed full-scale testing may only comprise a limited full-scale test, e.g. static test only, fatigue test only, test in one direction only, etc.

In general, adjustments and improvements that obviously strengthen the blade tend to reduce the need for renewed full-scale testing. Furthermore, changes only affecting areas with large safety margins should be less prone to trigger the need for renewed full-scale testing. However, changes that influence the loading of the wind turbine and thereby influence the design assumptions for the blade should be considered.

Some examples of adjustments and improvements in production and design typically requiring, or not requiring, renewed full-scale testing are given in Table A.1.

Table A.1 – Examples of situations typically requiring or not requiring renewed testing

Adjustments and improvements typically requiring renewed full-scale testing	Adjustments and improvements typically not requiring renewed full-scale testing
Modified profile shape around significant tested areas (for example, largest chord)	Modified blade tip shape
Shortening of some layers of fibers	Prolongation on some layers of fibers
Shift to a new type of resin or new type of fibers (e.g. shift from polyester to epoxy or from glass fibers to carbon fibers)	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. In the latter case testing on coupon level may be needed.
Shift to a new type of core material with different Young or shear modulus in sandwich constructions. (Often combined with a change in core material thickness).	Modification of the chamfer angle in some core materials in sandwich construction.
Major changes in stacking sequences in sandwich constructions	Minor changes in stacking sequences in massive laminates
Shift to a new production method (e.g. hand lay-up to injection)	Minor changes in the production process (e.g. adjustments on curing cycle)

Besides adjustments and changes to the blade structure, it may be the case that the design loads for a certain blade change after the full-scale test of the blade has been completed. In this case, renewed full-scale testing will only be needed if the design loads increase. When the design loads change, a new evaluation of the test loads against the design loads shall be conducted.

Annex B
(informative)

Areas to be tested

The following potential critical areas should be considered:

- the inboard part of the blade out to the span from where the section properties change only gradually;
- those parts of the blade where calculations show the smallest reserve factors against buckling, strength or fatigue life;
- if there is an aerodynamic braking device (or another blade system), that part of the blade incorporating this device, particularly where the structure is affected by this device.

No matter the testing methods used, achieving a proper load distribution in the outermost part of the blade is difficult. In most cases, this is not a major problem since the safety margin in a blade typically increases when approaching the tip.

In the light of the difficulties in applying a proper load distribution and the fact that testing of the outermost part of the blade may be less relevant due to large safety margins, it may be considered to cut the tip of the blade before testing.

Basically, cutting the tip should leave a sufficiently large part of the blade to enable testing of the sections where the lowest safety margins are present. If this is not the case, it may be considered to elevate the test loads in another blade section, principally alike the one with the lowest safety margin, in accordance with the method outlined in the following:

The test loads should be elevated by the factor f given by:

$$f = \frac{S_{\mathrm{ref}}}{S_{\mathrm{min}}}$$

where

f	is the load elevation factor;
S_{ref}	is the safety margin in the section used for verifying the strength of the section with the lowest safety factor;
S_{min}	is the safety margin in the section with the lowest safety margin.

The formula used for calculating the factor f shall be used for each of the failure modes considered and the maximum value of f shall be applied when determining the test loads.

In case the bolts used for connecting the blade to the hub or blade bearing forms an integrated part of the blade root (e.g. in case of T-bolt connections), full-scale testing of the blade should include the proper blade bolts with the intended pretension.

Annex C
(informative)

Effects of large deflections and load direction

Large deflections of a blade during testing typically lead to changes in load direction with magnitude.

The finite distance between attachment points for an actuator system in the laboratory and on the blade saddle implies that load direction angles will change when loading the blade. A longer distance normally reduces this change. The change in angle will result in a change to the load direction relative to the blade axis and the moment arm for calculation of the applied root moment and thereby also the moment at any point between the root and the load application point. This effect is sketched in Figure C.1.

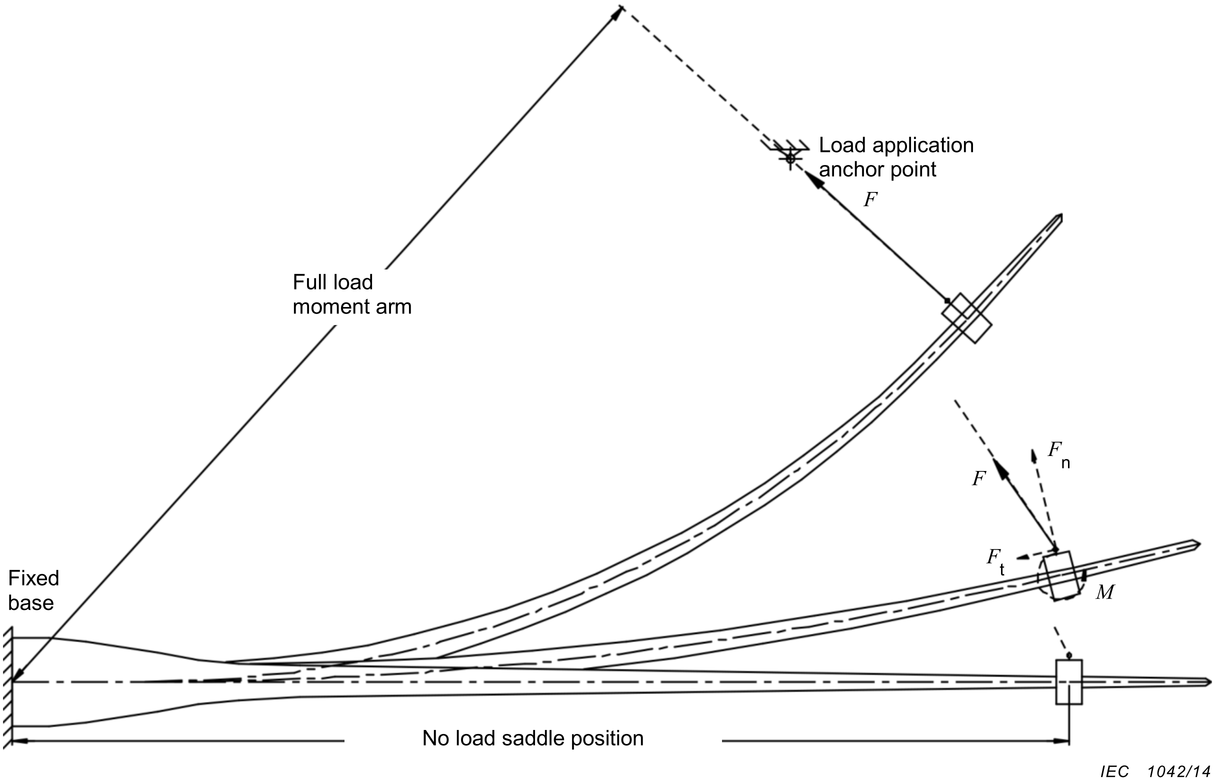


Figure C.1 – Applied loads effects due to blade deformation and angulation

In the case where the load application hinge line is not crossing the elastic axis of the blade, an additional moment is applied by the point load (see Figure C.1). This moment can also cause high local bearing pressure on the blade surface from the load introduction fixture.

In the case of a single axial load with the deformation perpendicular to the load, such as when the load is applied in the lead-lag direction and the blade also deforms in flap direction, changes in the load direction may also occur. Saddles not loaded perpendicular to the blade axis at high load may slip due to tangential forces (see F_t in Figure C.1). Such loading of saddles may also result in local prying forces that unintentionally overload the blade structure.

Multiple load introduction points could be used to minimize adverse loading conditions, especially at the higher load levels. Care shall also be taken to space saddles away from critical areas to be tested so that they are neither supported nor adversely influenced by the load introduction fixtures.

Annex D
(informative)

Formulation of test load

D.1 Static target load

To generate the load envelope representing the worst case, all simulated time points shall be post processed. The directions and magnitudes of the design loads shall be chosen such that they cover this full load envelope. The design loads then shall be augmented by factors that represent the uncertainties from the test load formulation, the simplification of the load application, the blade to blade variation, and the environmental effects during testing.

In the following example the load is limited to only flap and lead-lag loads. To check the blade resistance against the combined loading (lead-lag wise, flap wise), at any considered station the resultant load vector should be calculated. In many cases the resultant load vector in between the pure lead-lag and flap direction shows a higher value compared to the pure flap or pure lead-lag load direction. As an example in Figure D.1 a polar plot is given of the resulting bending moment for a typical blade. The envelope was generated using load data from 10 different conditions. The lines represent individual spanwise locations. The resultant load vector was considered 360° around the blade axis in 15° steps. It shows that testing in flap and lead-lag direction only will not cover all design loads.

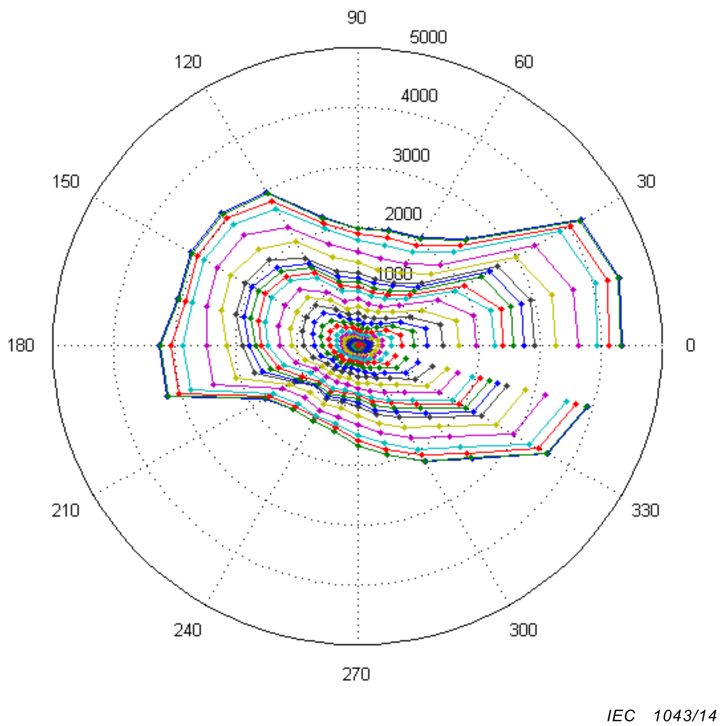


Figure D.1 – Polar plot of the load envelope from a typical blade

D.2 Fatigue target load

For each part of the blade that has to be tested, it has to be shown that the damage due to the test load is equal or higher than the damage due to the target load.

In order to determine the damage due to a load system, the load has to be translated into strain or stress. From these strain or stress cycles the damage can be calculated using an appropriate method of cycle counting and an appropriate fatigue formulation.

In order to avoid stacking of inaccuracies, the damage due to the test load and the damage due to the target load shall be evaluated using identical methods.

In practice, all parts of a blade cannot be properly tested. A criterion to determine the need to test a certain section of a blade can be the reserve against fatigue failure in that area. This determination should be made in accordance with the certifying body.

This reserve is generally expressed in the fatigue strain factor (*FSF*). This is the factor by which the load has to be multiplied to obtain damage equal to unity. Since the determination of the damage is a non-linear process, *FSF* has to be determined iteratively. For areas where this factor is high, a large reserve against fatigue damage exists and hence the need for testing this area is less urgent. If this factor is close to unity, the area is critical with respect to fatigue and testing is required.

In order for a given area to be properly tested, the damage due to the test load shall be equal or higher than the damage due to the target load. This means that the *FSF* for the fatigue test load shall be equal to or lower than the *FSF* for the fatigue target load.

The ratio between the *FSF* for the target load and the *FSF* for the test load can be defined as the relative *FSF* (*rFSF*):

$$rFSF = \frac{FSF_{\text{target}}}{FSF_{\text{test}}}$$

where

$rFSF$ is the relative fatigue strain factor;

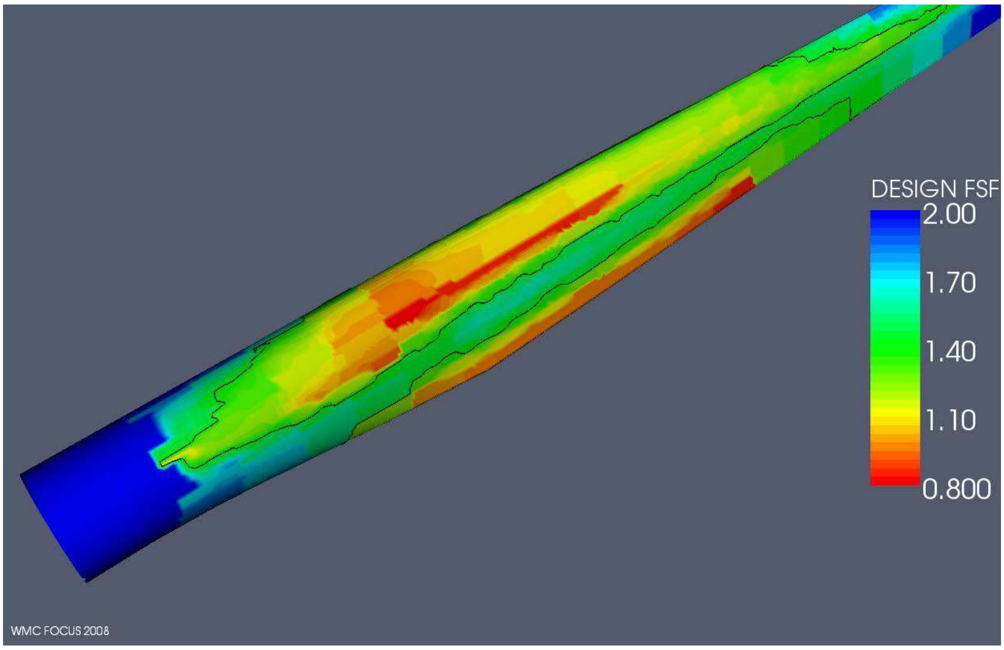
FSF_{target} is the fatigue strain factor for the target load;

FSF_{test} is the fatigue strain factor for the test load.

At all locations where the *rFSF* is bigger than unity the blade is properly tested.

As an example, the test load evaluation for a generic 62,5 m blade is given for two test methods. The examples given are only dealing with the stresses in the blade longitudinal direction and no attention is given to possible critical details and stresses in other directions. In the first part, the test load evaluation is given for a sequential single axial test, where the blade is sequentially loaded in pure flat and pure lead-lag direction. On the 62,5 m blade, strains are computed every 2 m of rotor diameter and on 26 locations distributed over the circumference of the chord for each spanwise location. From the resulting time series of strains in all these locations, together with the occurrences table and the fatigue life formulation, the damage and *FSF*'s are determined. The damage in each material is computed and at overlapping materials with different fatigue formulation the minimum *FSF* is considered. All computations are performed on the complete load set specified by IEC guidelines using an integrated wind turbine design tool.

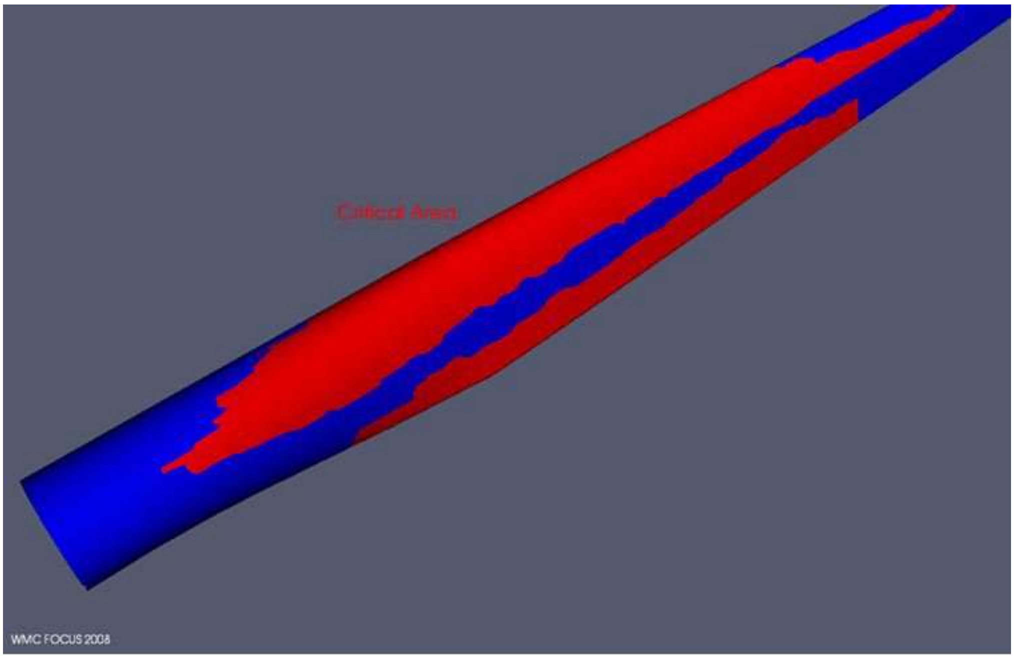
The damage in the blade after 20 years of service has been determined. The *FSF*'s are presented as contour plots in Figure D.2. Although arbitrary, it has been chosen in this example to consider areas with an *FSF* lower than 1,4 as critical.



IEC 1044/14

Figure D.2 – Design *FSF*

The black line in Figure D.2 connects the points where the *FSF* equals 1,4. The areas of the blade where this *FSF* is smaller than 1,4, should be tested. For clarity this area is represented as marked in red in Figure D.3.



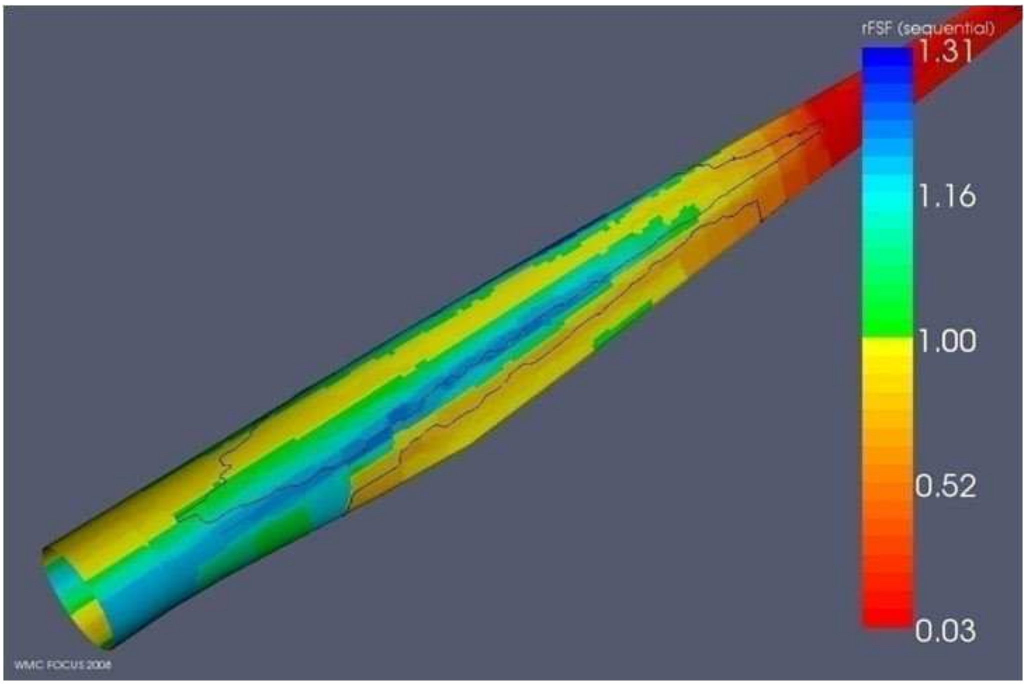
IEC 1045/14

Figure D.3 – Area where design *FSF* is smaller than 1,4 (critical area)

Areas where computation might underestimate stresses should also be considered, for example areas of high stress concentration in the bolted root connection, bonded joints of LE and TE and the area between the root and largest chord.

D.3 Sequential single-axial, single location

At a single location two separate loads are applied successively in the main directions, the applied loads are periodic. The load is applied at R = 40,0 m. The load due to acceleration of the blade mass is neglected. The number of test cycles for each test load was fixed to 1 million cycles. Figure D.4 shows the ratio of test and design FSF. In the graph the critical areas from Figure D.3 are also indicated with a black contour line. It also shows which amount of the critical area is tested, while locally in the critical area the blade is more than 30 % overloaded. This example concerns only a single load introduction point – not taking into account inertia effects. This can be improved by a more realistic load distribution.

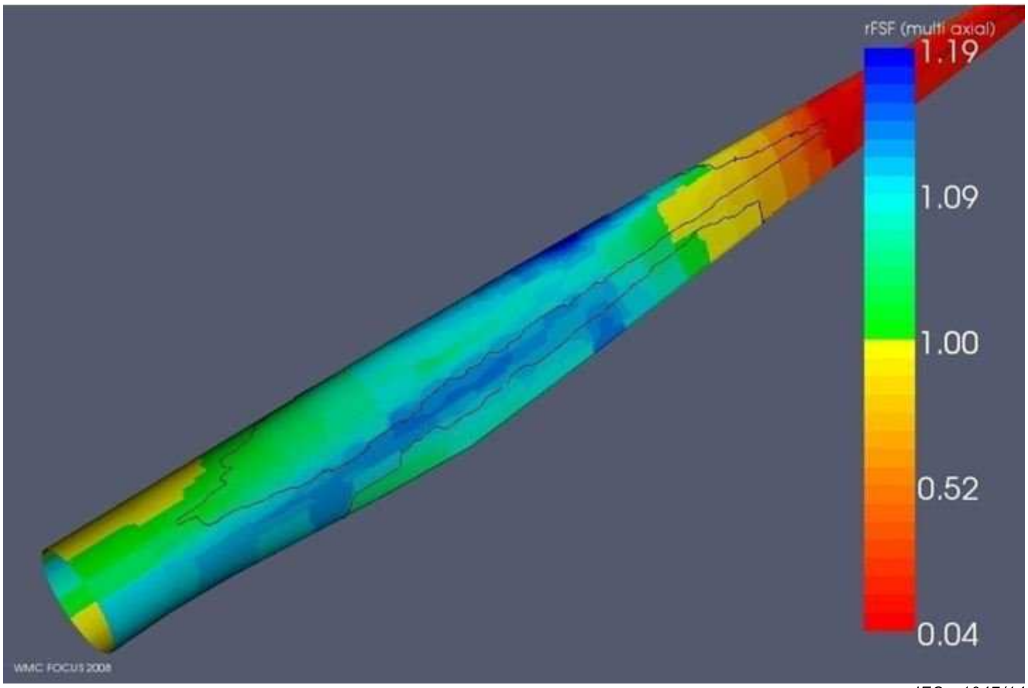


IEC 1046/14

Figure D.4 – *rFSF* and critical areas, sequential single-axial test

D.4 Multi axial single location

The second example is from a bi-axial test where on a single location a flat load as well as a lead-lag load is applied with a phase offset of about 90° so that the load introduction point describes an ellipsoidal trajectory in space. The *rFSF* contours are given together with the aforementioned critical area in Figure D.5.



IEC 1047/14

Figure D.5 – *rFSF* and critical area, multi axial test

It can be seen that for this type of test, a much bigger part of the critical area is tested, while the overload in this area is limited to 19 %. In this example, and with the arbitrarily chosen *FSF* value of 1,4 to define the critical area, it appears that for both types of test, parts of the critical area are not satisfactorily tested. However, as with the static test, it can be seen that with the fatigue test, combined loading (multi-axial) results in a considerably bigger part of the blade to be properly tested.

Annex E
(informative)

Differences between design and test load conditions

E.1 General

Ideally the testing performed on a wind turbine blade would recreate the design conditions of the blade. However, in practice there are a range of limitations on the tests that can be performed. As a result of these limitations some modifications and compromises are required in the static and fatigue testing undertaken on the blade. The following highlights some of the differences between design and test load conditions.

E.2 Load introduction

During a test, the load introduction is usually concentrated at spanwise blade sections. Due to the load concentration and possible reinforcement of the cross-section, expected deformations of the cross-section might be prevented, which would alter the blade stresses and/or strength locally. These load introduction points should therefore be located away from the areas specified to be tested (see 9.2 and Annex B).

E.3 Bending moments and shear

In a blade static test, loads are usually applied at a finite number of sections – whereas the ideal test load is distributed. This results in different spanwise distributions of section moments (see Figure E.1) and shear forces. The distribution of section moments can be improved by increasing the number of locations where load is applied; but this has the disadvantage of increasing the area of the blade that is disturbed. The objective is to replicate the target load as accurately as possible without compromising the validity of the test.

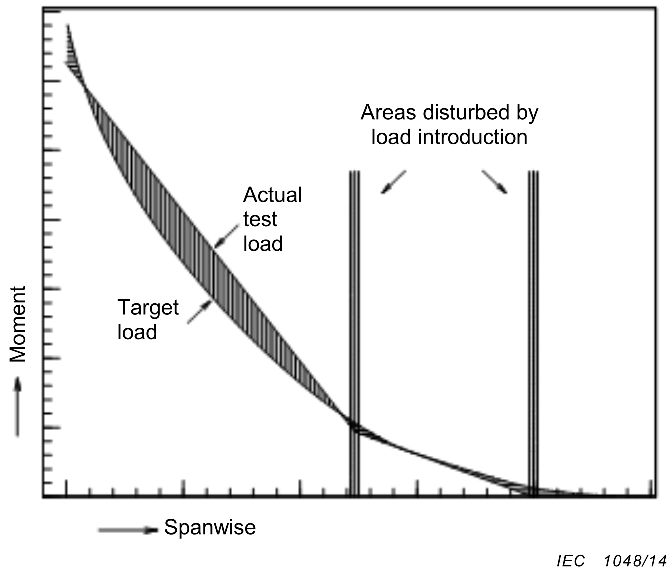


Figure E.1 – Difference of moment distribution for target and actual test load

E.4 Flapwise and lead-lag combinations

In static and fatigue tests, the results are most representative when combinations of flapwise and lead-lag loads are applied. By applying only the flapwise bending moment or only the lead lag moment, the resulting stresses and strains and/or damage rates may be lower in some areas than the target values (see Annex D).

E.5 Radial loads

Radial loads on an operating wind turbine blade arise due to the gravitational and centrifugal forces. Generally, the stresses caused by the radial forces are low.

E.6 Torsion loads

The magnitude of the torsion design loads shall be considered in the test loading. If torsion loads are significant in the structural design of the blade they should be included in the test (see 10.1.6.3).

In principle a representative multi-axial loading will result in a more realistic situation with respect to torsion loading than single axial-loading. For a straight blade, the flapwise-loading and resulting flapwise displacement means that any simultaneously acting lead-lag loading will introduce a torsion loading which increases toward the root. This is true for the real operational situation as well as for the representative multi-axial test loading.

E.7 Environmental conditions

The environmental and time conditions during testing are different from those in the design situation. These conditions might include:

- humidity;
- temperature effects;
- UV radiation;
- aging (interaction of fatigue and time);
- salinity;
- chemical contamination.

Relevant effects have to be considered in the evaluation by using the appropriate strength and fatigue formulation both for design and test conditions. However, the validity of the different design formulations for the different conditions is not tested.

E.8 Fatigue load spectrum and sequence

Fatigue testing is generally accelerated compared to in-service fatigue by applying a test load, which subjects the blade to sufficient fatigue damage within a reasonable test period (see 9.4 and Annex D).

Annex F
(informative)

Determination of number of load cycles for fatigue tests

F.1 General

This annex has been prepared in order to discuss the number of load cycles used by full-scale fatigue testing of rotor blades.

It is assumed that a test load factor covering errors in the fatigue formulation γ_{ef} of 1,05 is appropriate for fatigue tests aiming for a total of 1 million load cycles.

On the basis hereof, it is found that a γ_{ef} factor of 1,035 should be used for full scale fatigue tests loading the structure with e.g. 2,5 million load cycles. This result and others are summarized in Table F.1 below.

Table F.1 – Recommended values for γ_{ef} for different number of load cycles

Number of load cycles	γ_{ef}
5×10^5	1,065
1×10^6	1,050
$2,5 \times 10^6$	1,035
5×10^6	1,025
1×10^7	1,015

F.2 Background

The number of loads cycles applied to a rotor blade during full scale fatigue testing is, of course, a decisive factor for the duration of the fatigue test. Consequently, there will always be a wish to limit the number of load cycles as long as the test still fulfils its purpose with the intended trustworthiness.

On the basis of the coefficients historically used for calculating the test load factor, calculations are carried out in order to evaluate the influence of the number of load cycles in a full scale fatigue test on the test load factor.

F.3 The approach used

First of all consider the Goodman diagram in Figure F.1, which has been reduced to a single sided diagram for the sake of simplicity.

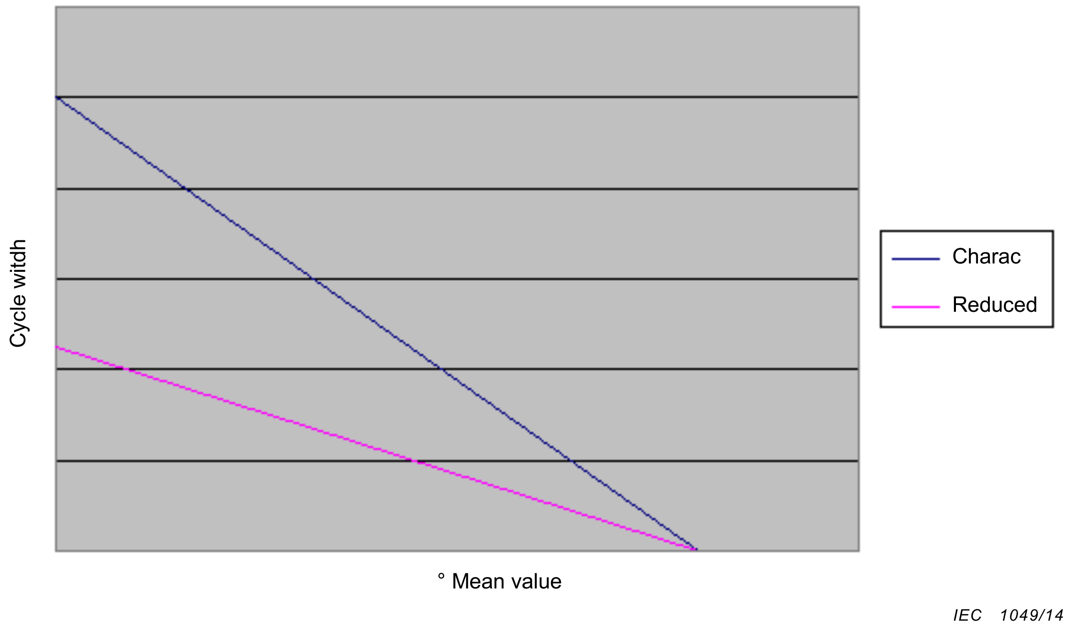


Figure F.1 – Simplified Goodman diagram

The line denoted “Charac” is based upon the characteristic strength values with intersection of the horizontal axis in a value representing the static strength of the structure S and intersection with the vertical axis in the dynamic strength valid for one single load cycle D.

The line “Reduced” is valid for a certain number of cycles n. This line also intersects the horizontal axis in the point S but the vertical axis is intersected in the point D_r, which is given by Formula (F.1).

$$D_r = \frac{D}{n^{\left(1/m\right)}} \tag{F.1}$$

where

D_r is the reduced dynamic strength valid for one load cycle;

D is the dynamic strength valid for one load cycle;

n is the actual number of load cycles;

m is the fatigue damage exponent for the material.

The damage for a certain load width W and load mean value M is given by the actual number of load cycles n divided by the allowed number of load cycles N, which is equal to the actual load width divided by the allowed load width to the power of m, Formula (F.2).

$$\text{Damage} = \frac{n}{N} = \left(\frac{W}{-\frac{D_r}{S} \cdot M + D_r} \right)^m \tag{F.2}$$

where

N is the allowed number of load cycles;

W is the load width;

S is the static strength of the structure;

M is the load mean value.

After inserting Formula (F.1) in Formula (F.2) and re-arranging, Formula (F.3) is obtained.

$$\text{Damage} = \left(\frac{W \cdot S \cdot n^{\left(1/m\right)}}{D \cdot \left(S - M\right)} \right)^{m} \tag{F.3}$$

The fatigue test is continued until the test damage, given by Formula (F.4) is equal to the target damage given by Formula (F.5) where subscript “t” refers to the test and subscript “0” refers to the calculated loads and thereby the target damage.

$$\text{Test Damage} = \left(\frac{W_{\mathrm{t}} \cdot S \cdot n_{\mathrm{t}}^{\left(1/m\right)}}{D \cdot \left(S - M_{\mathrm{t}}\right)} \right)^{m} \tag{F.4}$$

$$\text{Target Damage} = \gamma_{\mathrm{test}}^{m} \cdot \left(\frac{W_{0} \cdot S \cdot n_{0}^{\left(1/m\right)}}{D \cdot \left(S - M_{0}\right)} \right)^{m} \tag{F.5}$$

where

$_{\mathrm{t}}$ is a subscript referring to test values;

$_{0}$ is a subscript referring to calculated values;

γ_{test} is the test load factor.

Setting the test damage equal to the target damage, Formula (F.6) is obtained after some re-arranging

$$W_{\mathrm{t}} = \gamma_{\mathrm{test}} \cdot W_{0} \cdot \frac{\left(S - M_{\mathrm{t}}\right)}{\left(S - M_{0}\right)} \cdot \left(\frac{n_{0}}{n_{\mathrm{t}}} \right)^{\left(1/m\right)} \tag{F.6}$$

In order to investigate the sensitivity of W_{t} in relation to the fatigue damage exponent m, the derivative of W_{t} with respect to m is calculated, Formula (F.7).

$$\frac{\partial W_{\mathrm{t}}}{\partial m} = -\gamma_{\mathrm{test}} \cdot W_{0} \cdot \frac{\left(S - M_{\mathrm{t}}\right)}{\left(S - M_{0}\right)} \cdot \frac{\left(\frac{n_{0}}{n_{\mathrm{t}}} \right)^{\left(1/m\right)}}{m^{2}} \cdot \ln\left(\frac{n_{0}}{n_{\mathrm{t}}} \right) \tag{F.7}$$

The effect of changing from one number of load cycles n_{t1} in the fatigue test to another number of load cycles n_{t2} can be illustrated by R defined by Formula (F.8).

$$R = \frac{\frac{\partial W_{\mathrm{t}}}{\partial m}\left(n_{\mathrm{t}} = n_{\mathrm{t1}}\right)}{\frac{\partial W_{\mathrm{t}}}{\partial m}\left(n_{\mathrm{t}} = n_{\mathrm{t2}}\right)} = \frac{\left(\frac{n_{0}}{n_{\mathrm{t1}}} \right)^{\left(1/m\right)} \cdot \ln\left(\frac{n_{0}}{n_{\mathrm{t1}}} \right)}{\left(\frac{n_{0}}{n_{\mathrm{t2}}} \right)^{\left(1/m\right)} \cdot \ln\left(\frac{n_{0}}{n_{\mathrm{t2}}} \right)} = \left(\frac{n_{\mathrm{t2}}}{n_{\mathrm{t1}}} \right)^{\left(1/m\right)} \cdot \frac{\ln\left(\frac{n_{0}}{n_{\mathrm{t1}}} \right)}{\ln\left(\frac{n_{0}}{n_{\mathrm{t2}}} \right)} \tag{F.8}$$

where

R is the relative effect of changing from one number of load cycles (n_{t1}) to another (n_{t2});

n_{t1} is the first (reference) number of load cycles;

n_{t2} is the second (resulting) number of load cycles.

Suppose the total number of load cycles in the Markov matrix n_0 is 50 million and the fatigue damage exponent m is 9. If n_{t1} is 2,5 million and n_{t2} is 1 million, Formula (F.8) yields R = 0,7. It should be noted that the sensitivity of R to changes in n_0 and m is minor.

The test load factor to be used for fatigue testing is the product of 3 factors, where the γ_{ef} equal to 1,05 takes account of possible errors in the fatigue formulation, i.e. fatigue damage exponents deviating from the assumed values among others.

If a value of γ_{ef} of 1,05 is appropriate for tests with 1 million cycles, this 5 % increase in loads should be reduced to 3,5 % in case the test is extended to 2,5 million cycles instead since $0{,}05 \times 0{,}7=0{,}035$. The results for different values of the number of load cycles in a fatigue test are stated in Table F.2.

Table F.2 – Expanded recommended values for γ_{ef} for different number of load cycles

n_{t1}	R	γ_{ef}
5×10^5	1,3	1,064
1×10^6	1	1,050
$2{,}5 \times 10^6$	0,7	1,035
5×10^6	0,5	1,025
1×10^7	0,32	1,016
The values are calculated on the basis of Formula (F.8) using n_0 = 50 million, n_{t2} = 1 million and m = 9.		

The results given in Table F.2 are depicted graphically in Figure F.2.

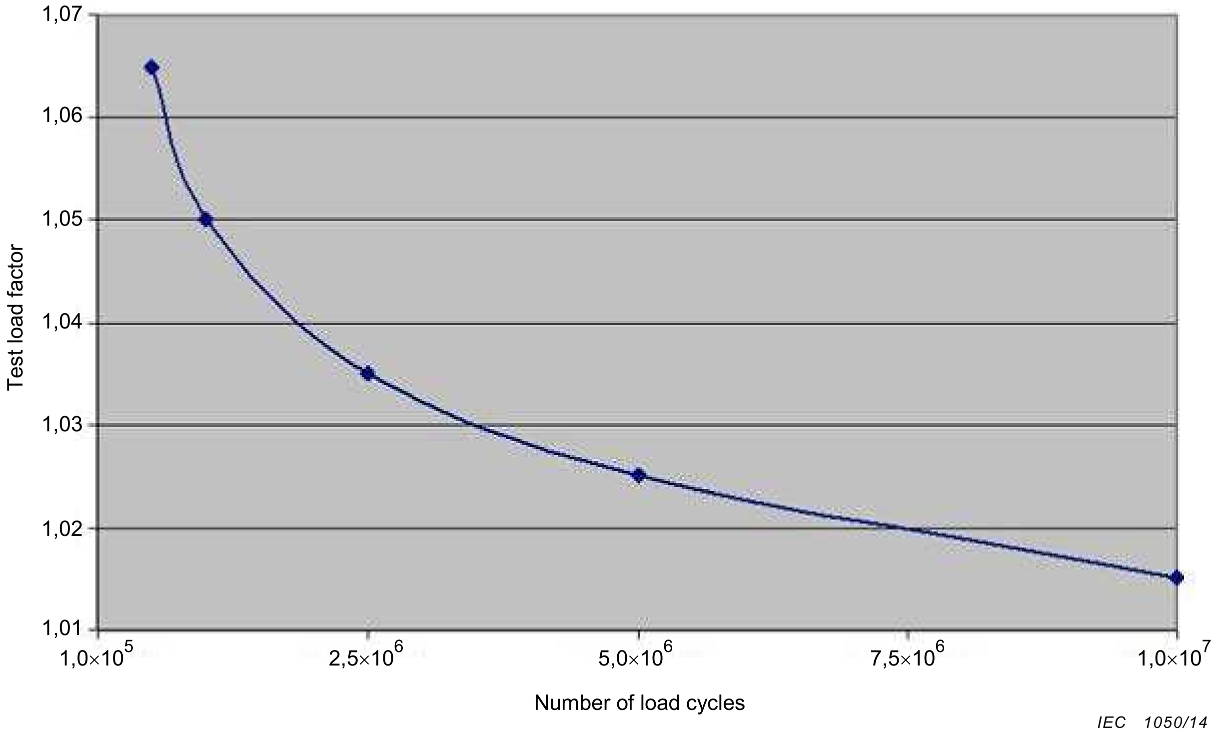


Figure F.2 – Test load factor γ_{ef} for different number of load cycles in the test

Bibliography

IEC 61400-22, *Wind turbines – Part 22: Conformity testing and certification*

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

3, rue de Varembé
PO Box 131
CH-1211 Geneva 20
Switzerland

Tel: + 41 22 919 02 11
Fax: + 41 22 919 03 00
info@iec.ch
www.iec.ch