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Wind turbine generator systems – Part 23: Full-scale structural testing of rotor blades

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Part 23:
Full-scale structural testing of rotor blades

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

WIND TURBINE GENERATOR SYSTEMS –

Part 23: Full-scale structural testing of rotor blades

FOREWORD

1) The IEC (International Electrotechnical Commission) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of the 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, the IEC publishes International Standards. 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. The IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
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- the subject is still under technical development or where, for any other reason, there is the future but no immediate possibility of an agreement on an International Standard.

IEC 61400-23, which is a technical specification, has been prepared by IEC Technical Committee 88: Wind turbine systems.

The text of this technical specification is based on the following documents:

Enquiry draft	Report on voting
88/116/CDV	88/137/RVC

Full information on the voting for the approval of this technical specification 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 3.

The committee has decided that the contents of this publication will remain unchanged until 2003. At this date, the publication will be

- transformed into an International Standard;
- reconfirmed;
- withdrawn;
- replaced by a revised edition, or
- amended.

Annexes A, B and C form an integral part of this technical specification.

Annex D is for information only.

Compliance with this technical specification does not relieve any person, organization or corporation of the responsibility of observing other applicable regulations.

INTRODUCTION

The blades of a wind turbine rotor are generally regarded as the most critical components of the wind turbine system. Many national standards address the blades separately in the design, but few require the testing of blades as a requisite for certification. Nevertheless, blade testing laboratories are currently operating in many countries throughout the world. Each laboratory has independently developed a unique set of test equipment, procedures and terminology that are used to test blades. Though each laboratory's techniques may be valid, the results of blade tests done at different facilities may be difficult to compare and evaluate.

The primary emphasis of the IEC TC 88 Working Group 8 effort was to identify commonly accepted practices among the various laboratories and to give guidance in establishing blade test criteria. Due to the wide range of methods (dictated by the test system hardware) used by the various laboratories, writing a restrictive standard that favoured one method to the exclusion of all others would not have been equitable. Therefore, the present technical specification has been written to provide guidelines on recommended practices. Many different methods are included.

The full collection of tests described in this specification should not be considered a requirement for every blade design. The need for tests will depend on the level of uncertainty in the design assessment due to the use of new materials, new design concepts, new production processes, etc. and the possible impact on the structural integrity. In some cases, alternative ways to perform a test are commonly used (see annex D). For the alternatives discussed in this specification, the advantages and disadvantages are noted.

WIND TURBINE GENERATOR SYSTEMS –

Part 23: Full-scale structural testing of rotor blades

1 Scope

This technical specification provides guidelines for the full-scale structural testing of wind turbine blades and for the interpretation or evaluation of results, as a possible part of a design verification of the integrity of the blade.

The following tests are considered in this technical specification:

– static strength tests;

– fatigue tests;

– other tests determining blade properties.

It is assumed that the data required to define the parameters of the test are available. In this technical specification, the 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 is outside the scope of this technical specification.

The technical specification is **not** intended to:

– form a detailed specification for the procurement of the test equipment;

– be a detailed work instruction covering all aspects of conducting a strength test;

– be used for establishing basic material strength or fatigue design data for blades and/or components;

– replace a rigorous design process;

– address the testing of mechanism function.

At the time this technical specification was drawn up, 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 WTGS configuration, size and material.

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this technical specification. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this technical specification are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references, the latest edition of the normative document referred to applies. Members of IEC and ISO maintain registers of currently valid International Standards.

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

IEC 61400-1:1999, *Wind turbine generator systems – Part 1: Safety requirements*

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

ISO/IEC 17025:1999, *General requirements for the competence of calibration and testing laboratories*

3 Definitions

For the purpose of this technical specification, definitions related to wind turbines or wind energy in general, given in IEC 60050-415 apply, as well as the following definitions, which are more specific to this publication.

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

3.2
blade
rotating, aerodynamically active part of the rotor

3.3
blade root
that part of the rotor blade that is connected to the hub of the rotor

3.4
buckling
failure mode characterized by a non-linear increase in deflection with a change in compressive load

3.5
chord
length of a reference straight line (the chord line) that joins, by certain defined conventions, the leading and trailing edges of a blade aerofoil cross-section

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

3.10
fatigue formulation
methodology by which the fatigue life is estimated

3.11
fatigue strength
measure of the load-bearing capacity of a material or structural element subjected to repetitive loading

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

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

3.16
full-scale test
test carried out on the actual structure or component

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

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

3.20
modal tests
test carried out to determine the natural frequencies, damping and mode shapes of a structure

3.21
natural frequency
(eigen frequency) frequency at which a structure will vibrate when perturbed and allowed to vibrate freely

3.22
non-destructive testing (NDT)
inspection methods that do not alter the properties of the structure

3.23
outboard
towards the blade tip

3.24
partial safety factors
factors that are applied to loads and material strengths to account for uncertainties in the representative (characteristic) values

3.25
point loading
load or series of loads that are applied at discrete spanwise positions

3.26
radial position
the distance from the rotor centre in a plane perpendicular to the rotor axis

3.27
R-ratio
ratio between minimum and maximum value during a load cycle

3.28
service loads
load spectrum, including sequence, which is representative of the actual operating conditions

3.29
S-N formulation
method used to describe the stress (S) vs. cycle (N) characteristics of a material, component or structure

3.30
spanwise
direction parallel to the longitudinal axis of a rotor blade

3.31
static test
test in which a specified load of constant magnitude and direction is applied to a test specimen

3.32
stiffness
ratio of change of force (or torque) to the corresponding change in displacement of an elastic body

3.33
strain
ratio of the elongation (or shear displacement) of a material subject to stress, to the original length of the material

3.34
tare loads
forces and moments created by gravity

3.35
tested area
region of the test object that experiences the intended loading

3.36
test load
forces and moments applied during a test

3.37
thickness
maximum distance, measured perpendicular to the chord, between the upper and lower surfaces of an aerofoil

3.38
twist
spanwise variation in angle of the chord lines of blade cross-sections

3.39
ultimate strength
measure of the maximum (static) load-bearing capacity of a material or structural element

3.40
variable amplitude loading
application of load cycles of non-constant mean, and/or cyclic range

3.41
Whiffle tree
device for distributing a single load source over multiple points on a test specimen

4 Notation

4.1 Symbols

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_{x}	lead-lag bending moment (rotor co-ordinate system)
M_{y}	flapwise bending moment (rotor co-ordinate system)
M_{z}	blade torsional moment (rotor co-ordinate system)
F_{a}	flatwise shear force (chordwise co-ordinates)
F_{b}	edgewise shear force (chordwise co-ordinates)
F_{c}	spanwise (tensile) force (chordwise co-ordinates)
M_{a}	edgewise bending moment (chordwise co-ordinates)
M_{b}	flatwise bending moment (chordwise co-ordinates)
M_{c}	blade torsional moment (chordwise co-ordinates)
D	theoretical damage
C	conversion factors for material strength
f	strength
F	load
q	strength parameter

4.2 Greek symbols

γ	partial 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
ff	fatigue load
fu	static load

k	characteristic value
m	material
n	consequence of failure
nf	consequence of failure in fatigue
nu	consequence of failure in fatigue
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 Abbreviations

SSF	Static strength factor
RSSF	Relative SSF
MSS	Minimum static strength
RMSS	Relative MSS
FSF	Fatigue stress factor
RFSF	Relative FSF
MFS	Minimum fatigue strength
RMFS	Relative MFS
WGTS	Wind Turbine Generator System(s)

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 strength and service life provided for in the design. It must be demonstrated that the blade can withstand both the ultimate loads and the fatigue loads to which the blade is expected to be subjected during its designed service life.

Normally, the full-scale tests dealt with in this technical specification 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 strength 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.

5.2 Limit states

To establish and evaluate the test load, a certain amount of information about the design must 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. Simply expressed, the limit state is the maximum load that a structure can sustain and still meet 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 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 9).

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.

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 result 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.

5.4 Results of test

The design loads form the basis of the test loading and the subsequent evaluation of the severity of the test loading. If no damage to the blade has occurred during the test and the blade structure and the test loading has been evaluated correctly, there is a strong indication that the blade design will fulfil its requirements. Nevertheless, one should be aware of what has been tested and what has not been tested.

5.4.1 What is tested

According to the design calculation, the blade must 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 a 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.

When a blade withstands the test without unexpected or severe damage, it gives some confidence that the design and production have no large errors leading to an unsafe situation. However, it is not an absolute proof, because it is possible that some errors in the design assumptions are compensating each other under the circumstances present during the full-scale test, whereas they might not under the actual operational circumstances.

5.4.2 What is not tested

During a full-scale test the following are not tested (and verified):

- the validity of the design loads;
- effects due to environmental conditions that are different during testing;
- the scatter in the results;
- possible changes in the production or design.

6 Blade data

6.1 General

In general, the blade shall be described by means of drawings, specifications and a parts list. Also, instructions for handling, lifting, and storage should be available.

There should be traceable documentary evidence for the design and construction of the test blade, for example, drawings, reference to a lamination scheme, and signed inspection reports. The blade itself should have a unique identification. In particular, if differences between the test blade and a series production blade exist, they shall be clearly documented.

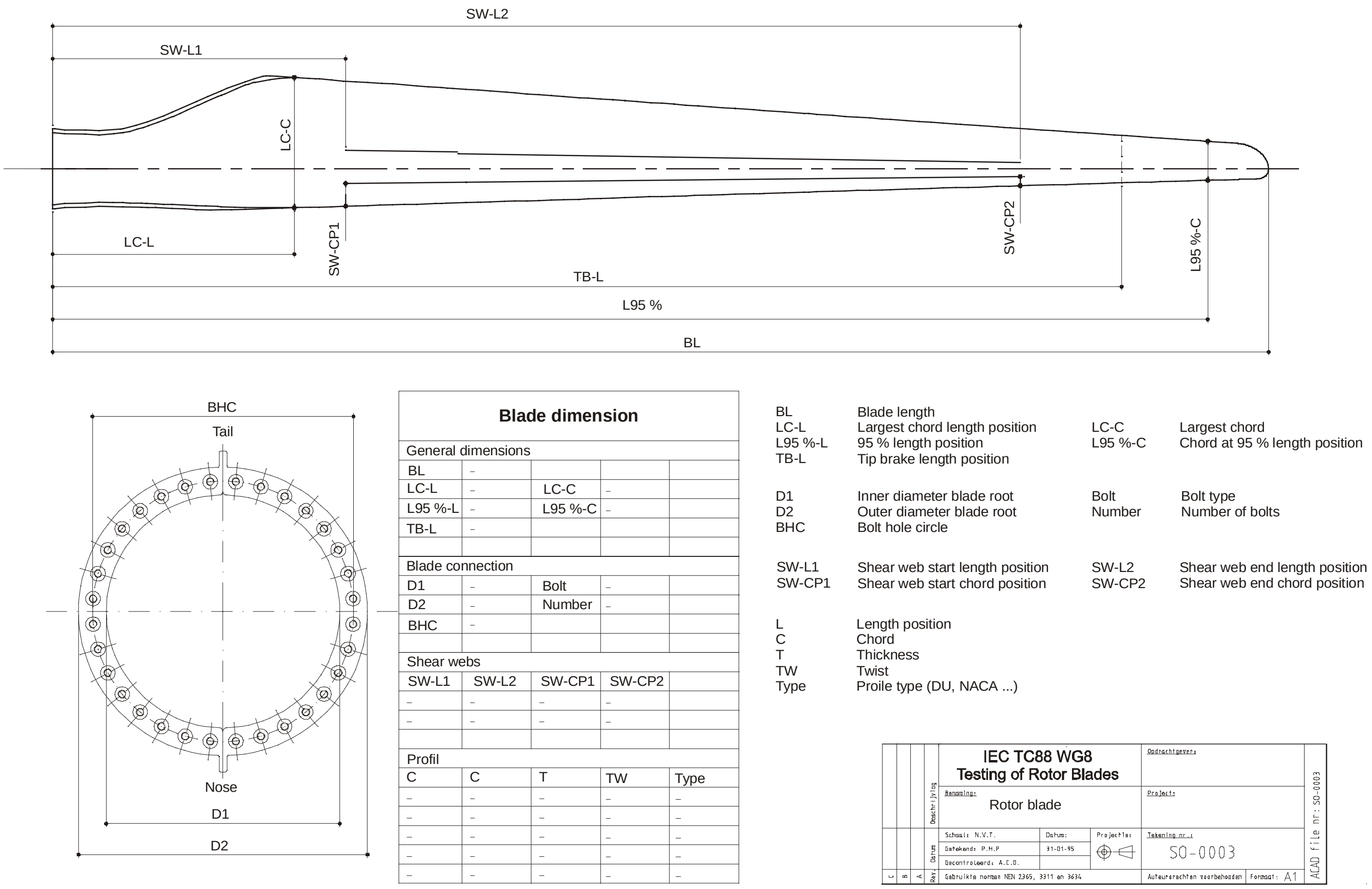
There is a great range of data required to completely specify the blade, which may be used by various parties. For example, the test lab must have basic dimensional data to determine if the blade will fit the test bed, whereas more detailed material information is required for evaluation and testing. These basic categories are described in the following lists.

6.2 External dimensions and interfaces

The dimensions of the blade shall be specified preferably in a drawing, giving at least the following data (for an example, see figure 1):

- blade length from blade root to blade tip;
- bolt pattern and blade root interface dimensions;
- chord and twist distribution.

For assessing the overall dimensional envelope and equipment needed to execute the tests, the maximum expected blade deflections and loads should be provided.



IEC 423/01

Figure 1 – Example of drawing showing the external dimensions and interfaces

6.3 Blade characteristics

In particular, the following should be specified for test and evaluation purposes:

- profile geometry, on at least five well-distributed locations of the blade including the load application sections;
- location and properties of major internal components;
- materials used (see 6.4);
- material distribution;
- essential manufacturing process characteristics;
- composition of laminated and sandwich structures;
- steel and metal components;
- fasteners;
- bonded joints;
- the following cross-sectional properties of at least five well-distributed locations on the blade:
  - elastic area,
  - principle bending stiffnesses,
  - position of principal axes,
  - torsional stiffness,
  - shear centre;
- total mass and mass distribution;

– location of the centre of gravity;
– natural frequencies (1st and 2nd flatwise and edgewise, and 1st torsional);
– tolerances on major properties.

For the strength-based tests the relevant strength at each chosen cross-section shall be given.

6.4 Material data

Appropriate strength and/or fatigue formulations and elastic properties for the materials used in the areas to be tested should be given. For fatigue, this includes appropriate S-N formulation(s), cycle counting procedures, an appropriate damage summation model, R-ratio effects, etc.

6.5 Design loads and conditions

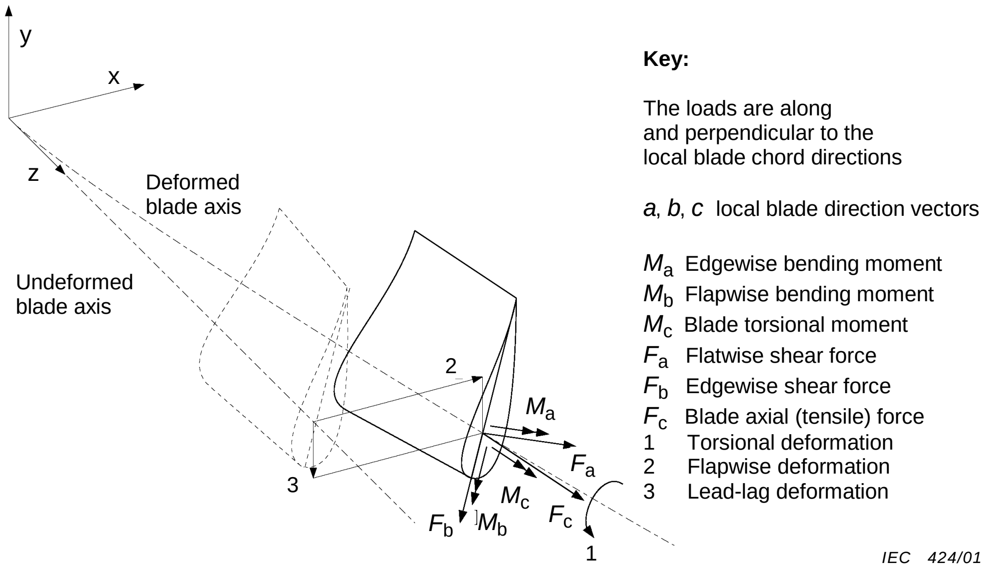
6.5.1 General

The test load is generally a reduction of the distributed aerodynamic and inertial blade moments into discrete forces positioned along the span that describes a particular load case. For load-based testing (see 8.2), the design loads shall be specified, whereas for strength-based testing (see 8.3) they are unnecessary. The standards applied and all partial safety factors included in the design loads shall be declared.

6.5.2 Load cases

Each design load case shall be defined with up to six load components (F_x, F_y, F_z, M_x, M_y, M_z) along the blade span with enough spanwise points to allow the test load to be accurately assessed at the critical areas to be tested. The six load components should be given, including phase and frequency information required to generate combined load cases[1)]. However, not all loads are of equal importance and not all loads can be applied during the test (see clause 7). The co-ordinate system relevant for the load components shall be clearly specified. Normally, either the chordwise co-ordinate system (see figure 2) or the rotor co-ordinate system (see figure 3) is used. For test purposes, the rotor co-ordinate system in figure 3 is recommended.

1) This is automatically fulfilled when the six components are given as time series.



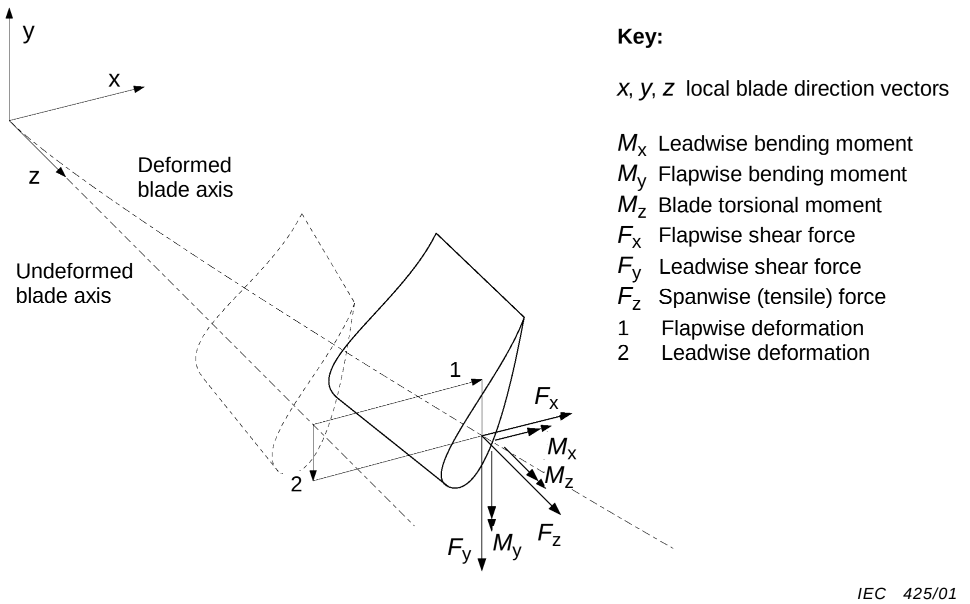
Key:

The loads are along and perpendicular to the local blade chord directions

a, *b*, *c* local blade direction vectors

M_a Edgewise bending moment
M_b Flapwise bending moment
M_c Blade torsional moment
F_a Flatwise shear force
F_b Edgewise shear force
F_c Blade axial (tensile) force
1 Torsional deformation
2 Flapwise deformation
3 Lead-lag deformation

Figure 2 – Chordwise (flatwise, edgewise) co-ordinate system



Key:

x, *y*, *z* local blade direction vectors

M_x Leadwise bending moment
M_y Flapwise bending moment
M_z Blade torsional moment
F_x Flapwise shear force
F_y Leadwise shear force
F_z Spanwise (tensile) force
1 Flapwise deformation
2 Leadwise deformation

Figure 3 – Rotor (flapwise, lead-lag) co-ordinate system (preferred)

6.5.3 Environmental conditions

In addition to the loads, the assumptions about the design operating conditions as well as the test conditions, which affect the material behaviour (e.g. humidity, temperature), should be specified.

6.5.4 Mechanisms

Loads on critical components such as tip brakes are often different in character from the general loads on the blades and may need extra specification and specific tests (see 8.7).

6.6 Areas to be tested

No single test can load the whole blade optimally. Representative loading should be applied to critical areas. The following potential critical areas should be considered:

– the inboard part of the blade out to the span 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, that part of the blade incorporating this device, particularly where the structure is affected by this device.

The areas to be tested should be specified.

6.7 Special blade modifications

Special blade modifications can be present for test purposes. During the fatigue tests the loads have to be magnified to do 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 specified.

6.8 Root fixing

In case the root area is considered for testing, the root assembly details shall be specified. This includes the bolt specification and tightening procedure, clamping length, hub stiffness, etc.

6.9 Mechanisms

If the structural interface to a mechanism is to be tested, it is preferred that the mechanism or a suitable fixture for introducing the load be supplied with the blade. Any additional data required to mount, position, and configure the mechanism or loading fixtures should be supplied.

7 Differences between design and test load conditions

7.1 General

The blade design will include the following load components:

– flatwise bending moment;
– edgewise bending moment;
– shear loading in flatwise direction;
– shear loading in edgewise direction;
– torsional moment;
– radial load.

However, laboratory testing necessarily has limitations. In a test, it is not practical to load the blade with all these components and to establish the same conditions as in the design. Beyond that, fatigue testing must be accelerated by increasing the test load above the design loads to expose the blade to sufficient fatigue damage within a reasonable test period. Other differences from ideal loading, such as concentrated load application, increased shear loading, and torsional loading should also be considered. Also, it is usually not possible to test all parts of the blade equally. The loading, though simplified, should be arranged to test at least the defined areas of interest.

In many cases, it may be necessary to modify the test load to account for differences between the test conditions and the environment assumed in the load or strength data sets (i.e. the laboratory environment is generally different from the design and operational environment). Appropriate factors are a matter for judgement and evaluation and are discussed in clauses 9 and 10.

In the following subclauses, some of the possible differences between design and test load conditions are discussed.

7.2 Load introduction

During a test, the load introduction is usually concentrated at spanwise blade sections (see 12.3). Due to the load concentration and possible reinforcement of the cross-section, normal deformations of the cross-section could be prevented, which would alter the blade stresses locally. These load introduction points should therefore be away from the areas specified to be tested (see 6.6 and 10.2).

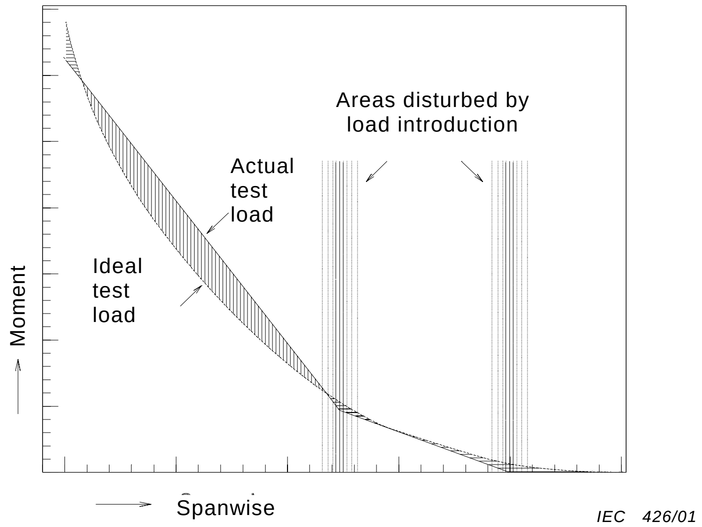


Figure 4 – Difference of moment distribution for ideal and actual test load

7.3 Bending moments and shear

In a test rig, the load will normally be applied at a restricted number of sections, whereas the ideal test load is continuous. This results in different spanwise distributions of section moments (see figure 4) and shear forces.

By increasing the number of cross-sections where the actuators apply the load, this can be improved. However, increasing the number of actuators also increases the blade area that is not properly tested (see 7.1 and 10.2).

Nevertheless, the spanwise distribution of moments and shear in the test has to follow the design load as closely as possible. In general, this is more important for the moment distribution.

7.4 Flatwise and edgewise combinations

In static and fatigue tests, the results are most representative when the combinations of flatwise and edgewise loads are applied. By applying only the flatwise bending moment or only the edgewise bending moment, the resulting stresses and strains and/or damage rates may be lower in some areas than the design values.

Particularly, if the stresses and strains are non-linear with the loads, and this is not taken into account in the evaluation, then the evaluation is in principle less accurate than when the flatwise and edgewise loads are applied simultaneously.

7.5 Radial loads

Radial loads on an operating wind turbine blade arise due to the gravitational and centrifugal forces. Generally, it is impractical to apply a well-distributed centrifugal load to a blade in the test rig without significantly altering the structure. The stresses caused by the radial forces are relatively low.

The radial forces in combination with bending can be significant (for example, for the root fixture). This can be compensated by adjusting the bending component appropriately.

7.6 Torsion loads

For most blades, the torsional moments are often small or negligible. If they are considered to be relevant, they may be applied. More commonly, unwanted torsional loads can be inadvertently induced by the test load apparatus (see 12.7.3). This influence should be evaluated.

7.7 Mechanisms

The dynamic environment of mechanisms located outboard on the blade is quite complicated. In these outboard regions, radial loads can have a dominant effect and should not be overlooked. In the absence of the radial loads in the test rig, the structural interface of a mechanism might not be tested appropriately. Therefore, special tests set up to include radial loads might be considered to test the structural interface. However, tests of the structural interface to such mechanisms will generally be limited to only the most significant components of the design loading, to keep complexity from becoming excessive.

7.8 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;
- ageing (interaction of fatigue and time);
- dust;
- 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. However, the validity of the different design formulations for the different conditions is not tested.

7.9 Load spectrum and sequence

The design loading is normally a set of load cases, with a variety of load cycles within each load case, based upon the actual stochastic loading. For practical reasons, the test load based upon the design loading is a further simplification. It can be a variable amplitude loading with a restricted variation of amplitudes or even a constant amplitude loading. Also the number of cycles in the test load is much less than in the design load. Because of this reduction in cycles and other effects, the load amplitudes and mean value are higher for the test load. As a result, the test load spectrum is very different from the design load.

Regardless of this difference, the test load and the design load can be equally severe. However, the conclusion about this will be dependent on the accuracy of the fatigue formulation (see 9.3.2 and annex B). Moreover, the sequence of the load cycles in the design load will be different as well. The sequence effect of the load cycles is normally not taken into account in the fatigue formulations. This is because the magnitude of the effect is not always fully known and even if known, it is rather complex to take into account.

8 Test loading

8.1 General

The design loads or design strength shall be clearly specified so that the test loads can be determined. The test load can either be load-based or strength-based. The load-based test can use either the complete design load envelope or a selected load case.

The purpose of the load-envelope testing is to show that the blade will sustain the intended loads without failure, and is normally used as part of a certification process. Load-envelope testing will necessarily involve a pre-test evaluation of the test load(s), which is covered in clause 10.

Selected-load testing uses some chosen loading distribution as its basis. Strength-based testing uses as-manufactured blade strength data as its basis. Both of these test types are normally used by the designer/manufacturer to determine the reserve strength by loading the blade to destruction [2][2].

8.2 Load-based testing

8.2.1 Design load-envelope testing

8.2.1.1 General

This type of testing is performed to demonstrate that the tested blade, within a certain level of confidence, has met the structural design requirements concerning its operating or extreme load conditions. Testing to destruction is neither sought nor required; rather the objective is to show that the blade can sustain the required loads without failure. Load direction may vary significantly for different load conditions, so for a given blade it may not be possible to test all of the critical load conditions and blade locations with a single test. The basis for the test loads is the entire envelope of blade design loads, derived according to generally accepted standards such as IEC 61400-1 or equivalent. This type of testing is the logical minimum for design verification.

For deriving the appropriate test loads, the loads are adjusted using the factors discussed in clause 9. The evaluation of these factors under load-envelope testing is done before testing. This process is discussed in detail in clause 10.

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[2] Figures in square brackets refer to the bibliography.

8.2.1.2 Static testing

In static testing, the blade should 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.

Because it is not expected that the blade will fail during design load-envelope testing, several successive tests may be used to completely test the blade. For example, if different orientations or load distributions are needed to represent different extreme load cases, each of these may be tested in turn. Within any such loading case, load introduction fixtures might be shifted, and load magnitudes changed, to ensure that all relevant blade areas are tested.

8.2.1.3 Fatigue testing

A test loading has to be generated giving fatigue damage equivalent to the design loads, on selected critical areas. 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. A more detailed discussion of the methodology and load factors to arrive at the final test loading is given in clauses 9 and 10.

Because it is not expected that the blade will fail during design load-envelope testing, the option exists to perform non-destructive static proof-loading tests, or a residual strength load-to-failure test, after the fatigue testing has been completed. This is one of the advantages of design load-envelope testing.

8.2.2 Selected-load testing

A blade-test load can be derived from a single chosen design load case. Generally, the blade is tested to static or fatigue failure with a loading distribution having the normalized shape of the design load. This yields the margin between that loading and the failure strength of the blade at its weakest location relative to those loads. This method may be used when the strength distribution of the blade is not known exactly, or when a comprehensive test load evaluation will not be done prior to test. Such a test may be preceded by other tests which do not result in destruction. For example, it might be used to determine residual strength after load-envelope testing, or fatigue strength after ultimate loading. Continuous or block loading increases are typically used to ensure timely failure.

Post-test evaluation can be performed to determine if the blade meets various use criteria, and what margin exists relative to those criteria. However, once a design load evaluation is done, it may be found that the applied test loads, versus the test loads required by the load evaluation, are not proportional at all blade stations. This could lead to inconclusive results if the final margins at failure are small. Also, this method only allows one load condition to be tested because the blade fails during the test. If the primary purpose of testing is to demonstrate that a blade meets its design criteria, the full methodology for load-envelope testing should be given first consideration.

8.3 Strength-based testing

8.3.1 General

Strength-based testing allows a direct verification of the blade strength, and an assessment of ways in which the design computations, and the resulting design itself, might be improved. This method can be used to find the lowest strength location, relative to expected strength, within a broad region. The loading is chosen to be proportional to strength for the greatest possible length of the blade in the region of interest. The nature of the strength distribution and the limitations of the test set-up will ultimately determine the size of the area tested to the strength distribution. Loading to either static destruction or to a fatigue loading level of interest, is then possible, with a large region of the blade seeing the desired condition relative to its expected strength.

Strength-based testing is particularly useful if the test loading type is desired to be different from that which determined the design, such as if a blade whose design was determined by fatigue operating loads is tested for extreme loading, or vice versa. For such cases, the blade strength distribution will often be quite different from design load cases that did not determine its design.

Another purpose for strength-based testing might be to assess the strength reduction between bulk material as it exists within the blade, and small coupons upon which material strength testing has been performed. Since both the coupons and the final blade can be tested under similar, controlled laboratory conditions, an assessment with minimal extraneous effects can be obtained. If a Whiffle tree or other multiple-point loading is used, then the load application points are chosen to produce a good fit between the shape of the loading curve and the shape of the strength curve. If a single point loading is used, then the loading point is chosen to provide a loading versus expected strength ratio that is highest in the region of interest.

Strength outside the chosen test region should be checked to reduce risk of damaging the test specimen due to failure in an unintended region. The loading distribution can often be adjusted if an undesired failure mode is seen to be possible. Conversely, loads that test failure strength in multiple regions in the same test may be intentionally provided, so that the one with the lowest strength relative to predictions will be found.

Strength-based loading will, by its nature provide long spanwise regions of relatively constant high stress. Thus, strain measurements may exhibit nearly constant values over a wide range of locations. If placed at or near structural discontinuities such as interior ply drops, the largest strains in the blade can be monitored. In locations of more uniform properties, typical bulk strains can be determined. In either case, the ability to create large regions of relatively constant strain may be used to help investigate features of interest.

8.3.2 Static testing

For a strength-based static test, the spanwise strength distribution of the blade against loading in the chosen orientation should be given. Care should be taken to ensure that the loading method will not lead to local buckling or excessive shears that were not intended. If checking the buckling stability is a test goal, a strength-based loading with appropriate orientation will provide large regions of high stress that can maximize the probability of driving the blade to its stability limit.

8.3.3 Fatigue testing

For fatigue testing, the strength distribution curve shall be based on the computed fatigue performance of the blade as a function of spanwise location. The fatigue effects of ply drops, altered material composition, and/or other structural details, which may have little effect in static loading, should be accounted for. These details may have a different fatigue behaviour. Therefore a single strength curve, with an adjustment factor for cycle level, may not be a suitable basis for all possible tests.

Loading direction changes may alter the failure mode as well as the strength curve, if different material types or structural features with different fatigue responses then become the limiting factor. Care should be taken to ensure that the strength curve is appropriate for the condition and orientation that is being tested.

8.4 Static-test load aspects

8.4.1 Load combination

If the blade is tested with combined loading, using both flatwise and edgewise components, the maximum load in one direction should be combined with the appropriate load(s) (not necessarily the maximum) in the other direction. In a load-envelope test, the maximum load in each direction should be imposed in turn, combined with appropriate load(s) in the other direction(s).

It should be noted that the blade may be most vulnerable to certain failure modes when a resultant load combination, which is not necessarily the highest in magnitude, is appropriately applied in a particular direction. For each load combination the blade should withstand the maximum load for the specified load duration (see 8.4.2).

8.4.2 Static loading duration

Since most common blade materials exhibit a reduction of strength with duration of load, the duration of the test load should 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 should be based directly on that. If there is some difficulty in assessing what duration of constant test load is a good match for the time history of the design load, 10 s is suggested as a minimum value. It is recommended that a value shorter than the design load duration be avoided as this would require the introduction and use of a strength reduction factor, and thereby introduce undesirable uncertainty in the interpretation of the test results.

8.5 Fatigue-test load aspects

8.5.1 Reduction of test time

The testing time has to be reduced for practical reasons. This can be done by the following modifications of the design load:

– increasing the frequency;
– omitting non-damaging cycles;
– increasing the load.

The possible test frequency (ranging from 0,5 Hz to 5 Hz) is often not much higher than the dominant frequency of the design load. Assuming the number of cycles in the design load is about 500 million for a 20-metre blade, testing at 1 Hz would take about 15 years, which is clearly not practical. Even if 2 Hz or 3 Hz is achieved, the time is still too long. So apart from increasing the frequency other modifications of the design load will also be needed.

The effect of omitting non-damaging cycles depends on the material (e.g. slope of S-N curve, fatigue limit, etc.). Analysis is needed to see what portion of the total cycles can be considered non-damaging.

Often the load has to be increased to obtain a practical test of perhaps 10 million cycles, or less for larger blades. This is a compromise between testing as realistically as possible, and obtaining a more reasonable testing time.

8.5.2 Limits to load magnification and frequency

Due to the considerations mentioned above, the design loads may have to be magnified to arrive at an appropriate test load. As the loads are magnified, the stresses and strains are increased. This magnification should lead to the appropriate theoretical equivalent fatigue damage accumulation. However, there are limitations to this. The maximum values of the stresses or strains might surpass the static strength of the material and consequently lead to static damage or failure.

Furthermore, 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. Resulting internal forces or structural movements which would not occur with a non-magnified loading may result in a test which is unrealistically severe or difficult to interpret.

Therefore, there are practical limits to the extreme values of stresses and strains during fatigue loading on the blade due to static strength and non-linearities. 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 (see figure 5).

Another problem with increasing the fatigue loading and frequency can be the internal heating of the highly stressed areas for some materials. This can also lead to accelerated fatigue damage.

Heating should be minimized to the extent that is practical and the temperature rise should be monitored and recorded when significant heating is unavoidable, so that its effect can be analyzed.

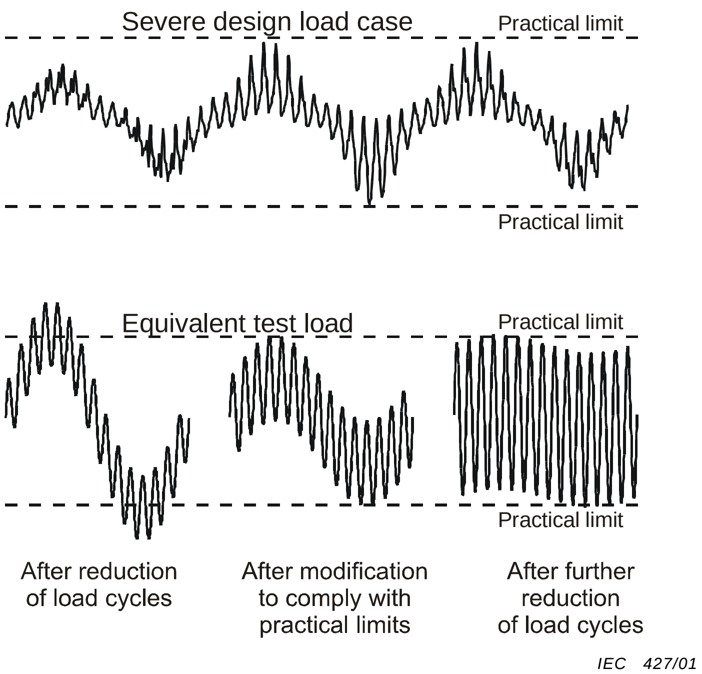

Figure 5 – Practical limits to load magnification

8.5.3 Type of loading

Many types of loading exist for fatigue testing. They can be:

- constant amplitude loading;
- block loading;
- variable amplitude loading;
- single-axial loading;
- multi-axial loading;
- multiple load points.

These types of loading are explained in 12.5.1.

8.6 Sequence of static and fatigue tests

The fatigue test can be performed on a rotor blade after it has been used for a non-destructive static test, such as a load-envelope test. This may not be valid for materials such as steel that can have improved fatigue behaviour after high loading. It is recommended that a residual strength test be performed after the fatigue test is completed.

8.7 Mechanisms

The loading of a mechanism and its mechanical interface may correspond to an overall blade loading case, or to a special device operational condition. For instance, a pivoting blade tip in its operational position could be loaded in a flatwise loading test, or in a specific test to apply loads for the deployed tip position (see also 6.5.4 and 7.7). In the first instance, where the mechanism and its mechanical interface are an integral part of the blade structural load path, the general considerations for the test load apply, as they would to any other area of potential interest. For structural tests with a mechanism in other conditions, such as a tip in the stopping position, appropriate adjustments or tests for that condition should be considered.

9 Load factors for testing

9.1 General

In testing, various load factors have to be taken into account. Those arising from the design are discussed in 9.2. 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 9.3.

9.2 Partial safety factors used in the design

9.2.1 General

In the design calculations, partial safety factors (or coefficients) have to be included. According to ISO 2394 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.

It appears that the product of the partial safety factors (γ_m, γ_n and γ_f) is similar in magnitude for many design standards [1]. However, some standards allocate more of the overall safety to one or other of these factors. For the design this makes no difference because all have to be applied. However in testing this makes a difference because only γ_f and γ_n will affect the test load. This is illustrated in annex A which includes an example of how to deal with this problem.

9.2.2 Partial factors on materials

General partial factors for materials γ_m, among other things, normally account for the uncertainties in the relation between the material properties in the structure and those measured by test control specimens, i.e. uncertainties in the conversion factors. In other words, the material strength and fatigue behaviour for the actual material in produced blades can be worse than the material in test coupons on which the strength and fatigue formulation is based. The loads should not be increased by this factor because the material in the blade being tested is the actual material.

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, ageing, temperature, etc. These will be applied implicitly using the appropriate strength and fatigue formulation during the evaluation (see 9.3.3 and 10.4.4).

9.2.3 Partial factors for consequences of failure

The partial factors for consequences of failure γ_n 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[3]. 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 fatigue test shall reflect this additional safety requirement. As a consequence, these factors shall be included in the test load.

9.2.4 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 must be able to resist the design load including the appropriate partial safety factors for loads.

9.3 Test load factors

9.3.1 Blade to blade variation

Often only one specimen is tested in a full-scale blade test as a final design verification and no information is gathered about the possible scatter in the actual blade strength. This presents a problem because there is no good way of knowing which portion of the production blade distribution the tested blade represents. A stronger than average blade test specimen taken from a population of blades having strengths below design strengths could be misleading if it was believed that the test specimen's strength was closer to average.

However, in a full-scale test in which the majority of the area of the blade is being subjected to a test load equivalent to the design load, many details and a large area are tested simultaneously. This is somewhat comparable to the testing of a number of small specimens under similar conditions and taking the data of the specimen that failed first as the test result. Statistically, this would mean that for the blade a lower mean with less scatter can be expected than for small-scale specimens. On the other hand, the damage accumulation in a blade can be slower due to stress redistribution as the damaged area becomes more flexible.

Nevertheless, less scatter can be expected as a larger area of the blade is equally severely tested. This is more closely realized in a test with multidirectional loading than with a single axial test.

If there is no failure probability distribution data available for the particular blade type, the following test load factors are recommended:

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

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

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

9.3.2 Possible errors in the fatigue formulation

Due to the conversion of the original fatigue design load to a test load, the severity of the test load with respect to the design load has to be evaluated (see clause 10). This evaluation for equal severity is done using the appropriate fatigue formulation. As the test load deviates more from the original design load (e.g. constant amplitude loading), this comparison becomes more and more dependent on the validity of the fatigue formulation (see annex B). The factor to compensate for this uncertainty (and which should be applied) is given by:

for fatigue tests: $\gamma_{ef} = 1{,}05$

This factor may be reduced if it can be shown that the evaluation of the test load compared to the design load is hardly affected by a variation of the characteristic values in the fatigue formulation (e.g. the slope of the S-N curve, R-ratio models, sequence effects).

9.3.3 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.

The test conditions are more benign than the design conditions, leading 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 10.4.4). Whenever the effect is given by factors, these can be used as a first guess for the factor necessary to magnify the load to arrive at an equivalent test load.

9.4 Application of load factors to obtain the target load

The design load including the partial safety factors on loads γ_f and multiplied by consequences of failure γ_n, and the test load factors γ_s and γ_e is considered as a starting point for the test load. This load is referred to as the target load (F_{target}). For the static and fatigue test this becomes respectively:

for static tests:

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

where

- $F_{target-u}$ is the target loading;
- F_{du} is the design loading (including partial factor for loads γ_f);
- γ_{nu} is the partial factor for consequence of failure;
- γ_{su} is the partial factor for blade to blade variation.

for fatigue tests:

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

where

- $F_{target-f}$ is the target loading;
- F_{df} is the design loading (including partial factor for loads γ_f);
- γ_{nf} is the partial factor for consequence of failure;
- γ_{sf} is the partial factor for blade to blade variation;
- γ_{ef} is the partial factor for errors in the fatigue formulation.

The test loading should ideally be equivalent to the target loading.

Further magnification of the loads will be required to cover the necessary modifications (such as a reduction of the number of cycles and different conditions). The amount of magnification needed will have to be checked by the evaluation of the test load distribution (see clause 10).

10 Evaluation of test load distribution in relation to design requirements

10.1 General

Because of the necessary modifications to obtain a practical test loading, and the different conditions in the laboratory compared to outdoor use, the test loading will be different from the target loading (see 8.4).

The distribution and/or the ratio between the load components of the test load will be different from the target load. Since the test must prove that the blade can survive the target loading, the test loading must 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. In carrying out this evaluation, it must be kept in mind that the differences as stated in clause 7 are still present.

10.2 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 these 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 one chord length on either side of the fixture.

10.3 Static tests

10.3.1 General

In the following subclauses, two possible approaches to evaluate the test load distributions for static tests are given. Each of them can be used to evaluate whether the test load is as severe as the target load. However, each one may correspond more closely to a particular design calculation approach, and it is thus easier to use. Other methods may also be appropriate.

10.3.2 Evaluation on the basis of load component distribution

The severity of the test loading compared to the target loading can be evaluated by a comparison of the six load components resulting from the test load versus the target load. For each cross-section where each of the section forces and moments resulting from the test loading is larger than those resulting from the target loading, the test is more severe than the target load. This means that these sections are sufficiently tested for static strength.

However, not all load components resulting from the design loads can be applied during the test for practical reasons (see clause 7). Furthermore, different critical stressed areas in the blade can result from different load cases. This makes the evaluation on the basis of load component distribution not always conclusive.

10.3.3 Evaluation on the basis of static strength factor

The evaluation can be done by comparing the static strength factor (SSF) for the target loading following from the design loads and conditions with the SSF for the test load and test conditions.

The static strength factor (SSF) expresses the reserve on the basis of stress or strain level. This SSF can be defined as follows:

the SSF is the factor by which the load or stresses have to be multiplied to arrive at the design strength of the material or structural detail.

For the SSF the following expression can be given:

$$SSF = \frac{f_{\mathrm{k}} / \gamma_{\mathrm{m}}}{\sigma} \equiv \frac{f_{\mathrm{k}}}{\sigma \times \gamma_{\mathrm{m}}} \qquad (3)$$

where

f_{k} is the characteristic strength;

σ is the applied stress or strain level;

γ_{m} is the partial material factor.

For the design and test loading and conditions this becomes respectively:

$$SSF_{\mathrm{target}} = \frac{f_{\mathrm{k\text{-}design}}}{\sigma_{\mathrm{target}} \times \gamma_{\mathrm{m}}} \qquad (4)$$

$$SSF_{\mathrm{test}} = \frac{f_{\mathrm{k\text{-}test}}}{\sigma_{\mathrm{test}} \times \gamma_{\mathrm{m}}} \qquad (5)$$

where

σ_{target} is the applied stress or strain level due to the target load;

σ_{test} is the applied stress or strain level for the actual test load;

$f_{\mathrm{k\text{-}design}}$ is the characteristic strength for design conditions;

$f_{\mathrm{k\text{-}test}}$ is the characteristic strength for test conditions.

By comparing the SSFs based on the actual test loading and the target loading, the severity of the test loading on the basis of load or stresses or strain is obtained. For a test loading to be at least as severe as the target loading at a particular location, the following must be true:

$$SSF_{\mathrm{test}} \leq SSF_{\mathrm{target}} \qquad (6)$$

The ratio between the SSFs can be referred to as the relative SSF (RSSF):

$$RSSF = \frac{SSF_{\mathrm{target}}}{SSF_{\mathrm{test}}} \qquad (7)$$

Substitution of (4) and (5) leads to:

$$RSSF = \frac{\sigma_{\text{test}} \times f_{\text{k-design}}}{\sigma_{\text{target}} \times f_{\text{k-test}}} \tag{8}$$

At all locations where this factor is equal to or larger than one, the test loading is at least as severe as the target loading.

The stress or strain level required to meet the criterion that RSSF is larger than one can be deduced as follows. From (8) it follows that for a test loading to be as severe as the target loading, the minimum required stress or strain level is given by:

$$\sigma_{\text{test}} = \sigma_{\text{target}} \frac{f_{\text{k-test}}}{f_{\text{k-design}}} \tag{9}$$

Assuming a linear relation between load and stresses or strain it follows from (1) that σ_{target} is given by:

$$\sigma_{\text{target}} = \sigma_{\text{design}} \times \gamma_{\text{nu}} \times \gamma_{\text{su}} \tag{10}$$

where σ_{design} is the stress or strain due to the design load.

Substitution of (10) in (9) leads to the following expression for the required stress or strain level during the test:

$$\sigma_{\text{test}} = \sigma_{\text{design}} \times \gamma_{\text{nu}} \times \gamma_{\text{su}} \frac{f_{\text{k-test}}}{f_{\text{k-design}}} \tag{11}$$

10.3.4 Evaluation on the basis of the minimum required strength

In principle, to be able to calculate SSF, the characteristic strength (f_{k}) of the relevant detail and/or material and the possible stress concentrations have to be known as a prerequisite. By evaluation on the basis of the minimum static strength (MSS) to survive the load, these values are not required.

The minimum static strength can be defined as follows:

> *the minimum static strength (MSS) is the required minimum value of the characteristic strength under a defined reference condition to survive the applied load (stress or strain) level.*

This value follows from:

$$MSS = \sigma \times \gamma_{\text{m}} \tag{12}$$

For the target loading and test loading, this becomes respectively:

$$MSS_{\text{target}} = \sigma_{\text{target}} \times \gamma_{\text{m}} / C_{\text{design}} \tag{13}$$

$$MSS_{\text{test}} = \sigma_{\text{test}} \times \gamma_{\text{m}} / C_{\text{test}} \tag{14}$$

where

C_{design} is the conversion from the defined reference condition to the design condition;

C_{test} is the conversion from the defined reference condition to the test condition.

These conversion factors are given by:

$$C_{\text{test}} = \frac{f_{\text{k-test}}}{f_{\text{k-ref}}} \tag{15}$$

$$C_{\text{design}} = \frac{f_{\text{k-design}}}{f_{\text{k-ref}}} \tag{16}$$

By comparing the MSS values following from the actual test loading and the target loading, the severity of the test loading on the basis of stresses or strains is obtained. For a test loading to be at least as severe as the target loading at a particular location, the following must be true:

$$MSS_{\text{test}} \geq MSS_{\text{target}} \tag{17}$$

The ratio between the MSS values can be referred to as the relative MSS (RMSS):

$$RMSS = \frac{MSS_{\text{test}}}{MSS_{\text{target}}} \tag{18}$$

Substitution of (13) and (14) leads to:

$$RMSS = \frac{\sigma_{\text{test}} \times C_{\text{design}}}{\sigma_{\text{target}} \times C_{\text{test}}} \tag{19}$$

In all locations in which this factor is equal to or larger than one, the test loading is at least as severe as the design loading. If the possible stress concentration factor is equal for all load components, the RMSS is independent of the actual value.

The stress or strain level required to meet the criterion that RMSS is larger than one, can be deduced as follows. From (19) it follows that for a test loading to be as severe as the target loading, the minimum required stress or strain level is given by:

$$\sigma_{\text{test}} = \sigma_{\text{target}} \frac{C_{\text{test}}}{C_{\text{design}}} \tag{20}$$

Substitution of (10) in (20) leads to the following expression for the required stress or strain level during the test:

$$\sigma_{\text{test}} = \sigma_{\text{design}} \times \gamma_{\text{nu}} \times \gamma_{\text{su}} \frac{C_{\text{test}}}{C_{\text{design}}} \tag{21}$$

Substitution of (16) and (15) in (21) will again result in (11).

10.4 Fatigue tests

10.4.1 General

Within the area to be tested, the severity of the test loading compared to the target loading will vary. For the fatigue test, this means that the equivalent severity for the test load and target load can be reached at a different number of fatigue cycles. Due to the fatigue characteristics of most materials this difference in time can be quite substantial, whereas the difference on the basis of load level is moderate.

When a certain area of the blade fails **after** it has been subjected to a test load equivalent 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.

By taking these considerations into account at the end of the test, it can be verified which locations have been subjected to an equivalent or more severe fatigue loading without failing before reaching the required performance. In principle, it has been proven that these locations are fatigue resistant enough.

It should be noted that the fatigue formulation and/or material factors applied for the design load and test load are not necessarily the same. The appropriate ones for the test and design conditions respectively should be used as explained in 10.4.4.

10.4.2 Evaluation on the basis of theoretical damage

For each location of the blade in which 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 test loading is equal to or more severe than the target load.

This is expressed by:

$$D_{\text{test}} \geq D_{\text{target}} \tag{22}$$

where

D_{test} is the theoretical damage due to the actual test load;

D_{target} is the theoretical damage due to the target load.

10.4.3 Evaluation on the basis of load or stress level

10.4.3.1 General

Areas, that did not fail and for which the calculated fatigue damage due to the test load is larger than the calculated fatigue damage due to the target load, have been demonstrated to be fatigue resistant enough. However, the factor between those two damages is difficult to interpret. It does not give a clear indication of by what factor the test load is more severe. This is because the value of the damage itself gives no clear indication about the severity of the loading on the basis of stresses or strains. Therefore, various factors are used to compare different load spectra or fatigue formulations on the basis of load or stress/strain level. These can also be used to evaluate the test loading with respect to the target loading. Two possibilities are given here. The choice may depend on the particular design calculation approach.

10.4.3.2 Evaluation on the basis of the fatigue stress factor

A fatigue stress factor (FSF) can be used to evaluate the severity of the target loads compared to the actual strength[4]. This FSF can be defined as follows:

> *the FSF^{D} is the factor by which the load or stresses have to be multiplied to arrive at the allowable damage rate D (normally one).*

This FSF expresses the reserve on the basis of the stress or strain level. By comparing the FSFs resulting from the actual test loading versus the target loading[5], the severity of the test loading on the basis of load or stresses is obtained. For a test loading to be at least as severe as the target loading at a particular location, the following must be true:

$$FSF^{\mathrm{D}}_{\mathrm{test}} \leq FSF^{\mathrm{D}}_{\mathrm{target}} \tag{23}$$

where

$FSF^{\mathrm{D}}_{\mathrm{test}}$ is the FSF value calculated for the actual test load;

$FSF^{\mathrm{D}}_{\mathrm{target}}$ is the FSF value calculated for the target load.

The ratio between the FSFs can be referred to as the relative FSF (RFSF):

$$RFSF^{\mathrm{D}} = \frac{FSF^{\mathrm{D}}_{\mathrm{target}}}{FSF^{\mathrm{D}}_{\mathrm{test}}} \tag{24}$$

At all locations where this factor is equal to or larger than one, the test loading is at least as severe as the target loading.

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[4] The terminology stress reserve factor (SRF) was used in bibliographic reference [4] for comparing the results of various design calculation. Later this factor was renamed fatigue stress factor (FSF) because a reserve is not always found.

[5] In most cases, it is possible to arrive at an explicit numerical expression for the FSF or MFS. It can be obtained by an iterative calculation procedure in which the Rkf is varied until the damage rate is equal to allowable damage D. It is not always possible to arrive at a damage which equals the allowable damage exactly due to the discontinuities in some fatigue formulations (e.g., fatigue limit). In that case the Rkf value, that by a limited variation gives a lower and higher damage, can be used.

10.4.3.3 Evaluation on the basis of the minimal required fatigue strength

In principle, to calculate the FSF, the fatigue strength of the relevant detail and material and the possible stress concentrations have to be known as a prerequisite. By evaluation, on the basis of the minimum required fatigue strength (MFS) to survive the load, the fatigue strength itself does not have to be known completely.

Usually the fatigue resistance of a material or detail is characterized by an allowable stress level at a particular number of cycles under defined conditions. This reference stress level can be regarded as a parameter (q_f) by which the fatigue strength is characterized.

The minimum required fatigue strength (MFS) can be defined as follows:

> *the minimum required fatigue strength (MFS^D) is the value of the fatigue strength parameter (q_f) for which the fatigue damage rate is equal to the allowable value D (normally one).*

By comparing the MFSs resulting from the actual test loading versus the design loading, the severity of the test loading on the basis of load or stresses is obtained. For a test loading to be at least as severe as the design loading at a particular location, the following must be true:

$$MFS^{\mathrm{D}}_{\mathrm{test}} \geq MFS^{\mathrm{D}}_{\mathrm{target}} \qquad (25)$$

where

$MFS^{\mathrm{D}}_{\mathrm{test}}$ is the MFSD value calculated for the actual test load;

$MFS^{\mathrm{D}}_{\mathrm{target}}$ is the MFSD value calculated for the target load.

Note that the characteristic fatigue strength parameter, q_f, in both fatigue formulations must be the same and independent of the different conditions.

The ratio between the MFS^D values can be referred to as the relative MFS^D (RMFS^D):

$$RMFS^{\mathrm{D}} = \frac{MFS^{\mathrm{D}}_{\mathrm{test}}}{MFS^{\mathrm{D}}_{\mathrm{target}}} \qquad (26)$$

In all locations where this factor is equal to or larger than one, the test loading is at least as severe as the target loading. If the possible stress concentration factor is equal for all load components, the RMFS^D is independent of the actual value.

Examples of this approach for the evaluation of test loads for wood/epoxy blades and glass fibre reinforced plastic are given in bibliographic references [5] and [1] respectively.

10.4.4 Fatigue formulation considerations

The blade used in the full-scale fatigue test is in principle the same blade as the blades subjected to the actual operational design loads. However, this does not imply that the fatigue formulation used in calculating the damage caused by the target load is the same as the one for calculating the damage as a result of the test loading. This is because a blade in a laboratory is governed by different circumstances than the actual blade on the turbine.

For instance, the fatigue behaviour of a material under humid conditions can be different from the fatigue behaviour under dry conditions (by a different value of a constant or of the slope of the S-N curve, etc.). If the test in the laboratory is carried out under dry conditions, the damage accumulated during testing should be calculated using the fatigue formulation for dry conditions and the damage during the design life should be calculated using the formulation that is valid for the operational conditions.

In principle, for the test loading, the fatigue formulation valid or most applicable for the test conditions has to be applied, whereas for the target loading the fatigue formulation valid or most applicable for the operational conditions has to be applied.

Since the test conditions are normally less severe than the actual operational conditions, the fatigue behaviour will be better. As a result, the test loading has to be more severe than the target loading to obtain an equivalent damage accumulation. This will require (on top of the load factors to compensate for reduction of load cycles) an extra factor on the loads during the test (see also 9.3.3).

10.4.5 Post-test evaluation

After the test, the cumulative damage may be computed using the appropriate damage model. The test result may then be restated as an equivalent number of cycles at the final loading level, or some other chosen loading level, such as that which represents one equivalent operational life. Alternatively, the damage model could be used to compute the maximum load that would be sustained for some chosen number of cycles. All of this hinges on the failure being material-property dominated, without significant test-induced effects such as local heating, de-bonding, buckling, excess shear, or other effects that may not scale properly using the damage model. However, when such effects are judged to be insignificant, the equivalent damage calculations can be reasonably accurate; those calculations can give a good estimate of the blade fatigue performance under other conditions, and thereby some confidence that the design is sound.

To increase insight when making any test evaluation, it is recommended that blade strains be measured at the critical areas to provide a more accurate knowledge of material strain and an added understanding of the material damage model interpreting the results.

11 Failure modes

11.1 General

Detection of possible damage or failure during the test can be difficult because of the complex structure of the blades, which means that important structural elements are hidden and difficult to inspect and monitor. Further, the blade material can suffer local damage without showing it.

In this clause, only irreversible property changes of the blade are addressed as failure modes. Whether or not the blade fails to meet certain design criteria or standards is not a subject of this clause; only possible failure modes that have to be monitored are described.

The following qualitative distinction of failure modes is used and defined in the following subclauses 11.2 to 11.4:

– catastrophic failure;

– functional failure;

– superficial failure.

Buckling of components is not considered to be a failure mode by itself. But because of its influence on internal strains and blade cross-sectional stiffness, buckling might initiate a failure mode.

Damage outside the tested area, that does not affect the strain distribution in the tested area, should be reported but is not considered to be a failure.

11.2 Catastrophic failure

The IEC 60050-415 definition of catastrophic failure is:

disintegration or collapse of a component or structure that results in loss of vital function which impairs safety.

The following examples can be considered as catastrophic failures:

– 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.

11.3 Functional failure

A functional failure is judged to have occurred when the particular component or assembly no longer functions within acceptable limits.

The following examples can be considered as possible functional failures:

– the stiffness of the blade reduces significantly and irreversibly (on the order of 5 % to 10 %[6]);
– after unloading, the blade shows a substantial permanent deformation[7]);
– substantial permanent change of cross-sectional shape;
– after unloading the blade, a mechanism is no longer capable of performing its design objective[8].

Whether an item from the above list is a functional failure depends on the specific design criteria, and should be evaluated on a case by case basis. In any event, these items are to be noted and reported for evaluation.

11.4 Superficial failure

A superficial failure is one with no immediate structural consequences.

The following examples can be considered as superficial failures:

– small cracks, not causing significant strength degradation or bond line weakening;
– gel coat cracking;
– paint flaking;
– surface bubbles;
– minor elastic panel buckling;
– small delaminations.

Superficial failures might become a functional or catastrophic failure over time in outside environmental conditions. In any event, these items are to be noted and reported for evaluation.

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6) The relevant percentage is dependent on the design constraints.

7) Thought should be given to the fact that visco-elastic materials could restore this deflection totally or partly during a certain recovery time.

8) Testing of the function of the mechanism is not part of this specification.

12 Test procedures and methods

12.1 General

This clause describes the various methods and procedures used to perform static and fatigue strength tests. Test methods for experimentally determining blade properties are described in clause 13. Tests to measure blade properties are commonly performed either in conjunction with the static test described in this clause, or separately, as needed.

Procedures for controlling, calibrating, maintaining, and inspecting measuring and test equipment should be kept and maintained (for example as described in ISO/IEC 17025 or equivalent). When possible an end-to-end check of the system calibration should be made to verify all system components. If necessary, the measured data should be corrected for systematic errors introduced by the test set-up or test geometry.

12.2 Test stand and root fixture requirements

All strength tests require an appropriate mounting surface to attach the blade and react the test loads, and some means of applying the test loads. For practical reasons, the blade root is usually fixed to a test stand and the blade is loaded normal to its axis, applying the test load along the span of the blade. The blade is attached using a fixture to adapt the blade's bolt pattern to the test stand.

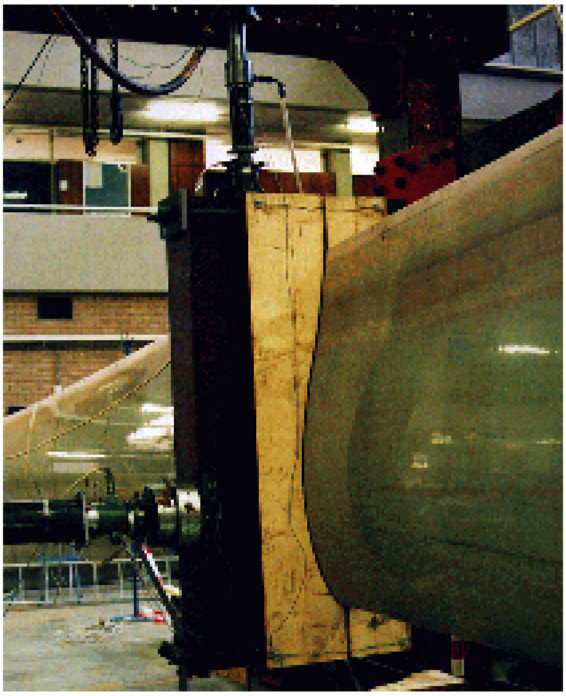
If validation of the root design is required, the root fixture should create a representative distribution of stresses in the blade root, with the same stiffness as the blade/hub attachment. It may be preferable to include the actual portion of the hub/blade interface to which the blade root is directly mounted (e.g. pitch bearing). If the tightening procedure and/or clamping length of the bolt or studs is different from the fasteners used on the wind turbine it should be documented and accounted for.

12.3 Load introduction fixtures

The blade should be protected at the load application point(s) to prevent local damage caused by load transfer from concentrated pressure at the skin contact area and from high shear loading. This can be achieved by constructing an external sleeve around the blade between the load source and the blade skin to distribute the load while preventing cross-sectional deformation (see figure 6). This method of attachment is usually removable, and does not permanently alter the blade's structure. Therefore, it is possible to test this area of the blade at a later time.

For point loading, when the load point will not be moved, the blade structure may also be reinforced internally to prevent local crushing of the section. Caution should be used to avoid changing the blade stiffness near the area to be tested.

Internal reinforcement is usually irreversible and will permanently alter the blade structure and the natural frequencies, making it impossible to test the modified area.



IEC 428/01

Figure 6 – Blade attachment fixture using an external sleeve of wood.

12.4 Static strength test

12.4.1 Type of loading

12.4.1.1 General

The blade can be loaded either with a surface load or with concentrated point loads (single/multi-point loads). Each method has advantages and disadvantages which are summarized in table 1. The method used will usually be determined by practical considerations discussed below.

12.4.1.2 Distributed surface loads

A continuously distributed surface load may be applied along the length of the blade using a heavy material (e.g. sandbags). The weight is distributed continuously along the blade span on the tension side of the blade in the orientation to be tested. Uniformly distributed loads can be achieved without large step changes along the span. This method will give the most representative distribution of shear forces along the blade span and can give an accurate representation of the load distribution.

This method can be difficult to use because of the problems associated with handling large masses. Because of the large added mass, the system's natural frequency is very low at extreme loads. This makes the blade/mass system easy to excite dynamically. At failure, weighted surface loads can give a higher energy release because the load continues to be applied after the initial fracture. This method is limited to single-axial static loading.

12.4.1.3 Single-point method

The application of a single concentrated point load at a spanwise location will generate a linear bending moment distribution. The linear distribution can approximate the target test load distribution over segments of the entire blade span. Usually, this will require progressive loading of the blade, applying forces several times at different spanwise locations, to achieve the target test load at all necessary locations. This can reduce the amount of equipment required.

The general procedure involves first loading the outboard blade segment to the corresponding test load. Then the load point is moved inboard and the next segment toward the root is loaded.

This method will generate higher shear loads in the blade at inboard load points than those generated by multiple-point loading or distributed surface loads.

This method may not be practical for a load-to-failure test, but it is possible. The load sequence is applied several times, increasing the load level a small percentage each time until a failure occurs. If the load steps are small enough the result will be approximately the same as a multiple-point load test.

12.4.1.4 Multiple-point method

Using multiple-point loading, the desired test load distribution (moment and shear) can be applied to the blade all at one time. This method provides a more realistic load match in shear than single-point loading. A full-span distributed load applied simultaneously at multiple spanwise locations may be advantageously used to perform a load-to-failure test to determine the ultimate strength, design margins, or buckling limit because most of the blade can be tested at one time.

It is important that the load at each point is increased uniformly to maintain the shape of the load distribution as the load increases. This can be done by connecting each of the load introduction points to a Whiffle tree or to individual loading devices, which increases the amount of hardware needed. Caution should be taken to avoid placing the attachment points in critical areas of interest because the load attachment areas are affected as described in 10.2. Load introduction areas can be tested later by removing load fixtures in critical areas one at a time and re-testing the attachment area.

12.4.2 Test control methods

Static test loading usually involves the application of a monotonically increasing load sequence. For a given load sequence, the static load is normally applied in even steps, or steadily increased at a controlled rate. The rate of loading may be prescribed as part of the test load along with the maximum level, if required. In general, the loading shall be slow enough to avoid dynamic effects that may cause load fluctuations that could alter the test. Errors in the test load may also be introduced because of changes in test geometry as the load increases, and by the masses of the test system apparatus. Corrections for these effects are covered in 12.7.

12.4.3 Loading devices

The loading devices commonly used for static blade testing are:

– overhead cranes or hoists;

– hydraulic or pneumatic actuators;

– dead weights (such as sandbags);

– winches.

Other equipment is sometimes required to modify or distribute the primary load onto different points on the blade. Some of these devices are:

– Whiffle trees and spreader bars;

– rocker arms and levers;

– pulley and cable systems.

Some examples of these devices are given in annex D.

12.5 Fatigue testing

12.5.1 Type of loading

12.5.1.1 General

There are many ways to load a blade in fatigue testing. Loads can be applied at a single point or at multiple points. Bending loads can be applied to a single axis or about two or more axes. The load can be of constant amplitude and frequency or variable. Each type has advantages and disadvantages. The type of loading used will often be dependent on the test equipment used.

12.5.1.2 Constant amplitude loading

In constant amplitude testing, the test load is characterized by a single-load cycle that is repeated many times, and in which the maximum and minimum load values are fixed. Constant amplitude blade test data are generally easier to compare with material coupon data because they are commonly determined using the same method. With constant amplitude testing, non-linear failure modes are easier to avoid when loads are amplified to accelerate tests. Constant amplitude tests ignore the possibility of load sequence effects and will introduce some additional uncertainty because of their sensitivity to the fatigue formulation (see annex B).

12.5.1.3 Block loading

Block loading is a variation of constant amplitude testing where the load is changed one or more times after a prescribed duration of constant amplitude cycles. One objective can be to generate a fatigue failure by applying blocks of load cycles at progressively increasing amplitudes. If the blade survives a block of cycles, the load is increased by a prescribed amount and a new block of cycles is applied. This process is repeated until a failure causes the test to stop. This loading type allows a test to be conducted at a reasonable load level to qualify a blade's design (such as with a design-verification test). However, increasing the load allows the test to be accelerated further to determine the failure life, likely failure mode, and design margins or reserves.

The contribution of damage from each load block can be computed using Miner's rule. Block loading is generally used with constant amplitude loading. The load should not be increased above the level that would alter the failure mode from the expected failure mode during normal operation.

Another variation of block loading is variable block loading where load blocks of various amplitudes are alternately applied. The objective of variable block loading is to introduce some sequence characteristics to a constant amplitude test when continuous variable amplitude loading is not possible.

12.5.1.4 Variable amplitude loading

In variable amplitude loading, the load is characterized by a series of load cycles with different magnitudes and mean values. The load series is typically repeated many times but the load spectrum may contain a range of load amplitude ratios and magnitudes. These spectra are more difficult to compare with coupon data taken at constant amplitude. Load amplification may be more difficult for variable amplitude loading because there are limits to load magnification (see 8.5.1). Variable amplitude loading gives the highest accuracy in matching the design load spectrum because the fatigue computation is not as sensitive to uncertainty in the fatigue formulation (see annex B).

12.5.1.5 Single-axial loading

This type of loading simplifies the loading using a single actuator or load source but does not allow the load direction to change. In single-axial loading, the fatigue load components may be applied separately or combined (e.g. flap and lead-lag) to give one resultant load. Applying the components separately requires two tests to be conducted. However, using two separate tests will not result in fatigue damage that is equal to the case of applying the loads simultaneously, as with multi-axial loading.

Applying the flap and lead-lag components simultaneously requires these components to occur in phase. Because there is only one axis of bending, tests conducted using single-axial loading will stress the extreme fibres farthest from the bending axis more severely, but will under-load the regions closer to the neutral axis.

Single-axial loading can be used with constant or variable amplitude testing.

12.5.1.6 Multi-axial loading

In multi-axial loading, the fatigue loading components, such as flap and lead-lag bending, are applied independently using separate loading devices. The phase relationship between the load components should be known and controlled throughout the test. This method is more representative of the actual stress distributions around the cross-section of the blade during operation. With two axes of bending, fibres near the neutral axis of one load component are stressed from the other bending direction. Multi-axial loading can be used with constant or variable amplitude testing.

12.5.1.7 Multiple load points

For simplicity, a single spanwise load introduction point is often used in fatigue testing. A single point can generally test a large portion of the blade span, but not the entire length. To increase the length of the blade test section or the accuracy of the moment distribution, multiple points along the blade can be used to introduce the load. This greatly increases the test complexity but it may be necessary to involve all of the critical regions of the blade for a single load combination.

12.5.1.8 Resonance loading

Resonance loading is achieved by exciting the blade at a frequency close to the natural frequency of the blade. As the spanwise load distribution follows the mode shape of the blade, the desired load can be obtained by adding mass in selected areas, and so, a large part of the blade can be tested in one test. Resonance loading is often used for single-axial, constant amplitude loading, but with certain limitations it may also be used for variable amplitude loading by changing the excitation frequency.

12.5.2 Test control methods

12.5.2.1 General

There are three basic test control methods that are in widespread use at the present time. In principle, the control method used is not dependent on the type of loading used. This subclause does not cover specific hardware or test set-up configurations. These are covered in annex D.

12.5.2.2 Displacement control

Under displacement control the blade deflections are controlled independently of the load being applied. Displacement control may be necessary when test frequencies are near (within about 20 %) the blade natural frequency. In these cases, blade dynamic effects will change the applied force from its static level. In a linear-elastic structure, this is not a problem as the quasi-static load and stroke are proportional, and load can be determined from the dynamic displacement levels. The blade stiffness should be monitored and the displacement range will have to be adjusted if significant changes occur. Creep may also require the displacement mean to be adjusted.

Test frequency can be varied over a range of speeds from quasi-static loading to beyond the first natural frequency. Most tests are run below the first natural frequency to maintain dynamic stability and to minimize thermal effects.

12.5.2.3 Force control

Force control uses the applied load to determine the movement of the blade. The force is applied independently of the blade displacements or natural frequencies. If the blade weakens or fails, the force remains constant, which causes higher displacements. Additional measures should be taken to monitor and control these displacements. Force control can be used when the test frequency is sufficiently below the natural frequency of the tested system to ensure minimal dynamic influence. Force control is most appropriate when displacements are small or when displacements are not linearly dependent on the load.

12.5.2.4 Resonance testing

The principle of the resonance test method is to excite the test blade in a narrow frequency range just below the natural frequency of the test blade. Additional mass is attached to the blade to achieve the desired mean load. Keeping the frequency just below the natural frequency, the amplitude of displacements can be adjusted by varying the exciter frequency. Blade resonance can be achieved by attaching an exciter to the blade or by moving the base at the blade's fundamental frequency. Large changes in the ambient temperature may cause changes in the blade stiffness and in the mean deflection of the blade, which may require adjustments to the test. Blade loads are controlled by directly maintaining deflections or strain within a specific tolerance range or indirectly using accelerometers.

12.5.3 Loading devices

The following types of equipment have been used to conduct fatigue tests on wind turbine blades:

– eccentric rotating mass;
– hydraulic actuators;
– camshaft.

A more complete description of the loading devices is given in annex D.

12.6 Advantages and disadvantages of test alternatives

In table 1 the disadvantages of the test alternatives described above are summarized.

Table 1 – Advantages and disadvantages of test alternatives

Test alternative	Advantage	Disadvantage
Distributed surface loading (using dead weight such as sandbags, etc.)	Accurate load distribution Shear load distribution is very accurate	Only single axial Only static loads Failure energy release can lead to more catastrophic failure Very low natural frequency
Single-point loading	Simple hardware	Only one or two sections at a time are accurately tested Shear loads are higher due to test load
Multiple-point loading	Larger part of the blade tested in one test Shear forces are more realistic	More complicated hardware and load control
Single-axial loading	Simpler hardware	Limited in achieving the correct strain/damage distribution over the whole cross-section
Multi-axial loading	Possibility to make load combinations of flap-wise and edgewise loads more realistic	More complicated hardware and load control
Resonance testing	Simple hardware Low energy consumption	Limited in achieving the correct strain/damage distribution over the whole cross-section
Constant amplitude loading	Simple, fast, lower peak loads	Sensitive to accuracy of fatigue formulation
Constant amplitude progressive block loading	Limited number of cycles to failure	Sensitive to accuracy of fatigue formulation and sequence effects
Constant amplitude variable block loading	Simple method to simulate variable amplitude loading	Sensitive to accuracy of fatigue formulation and sequence effects, although less than for constant amplitude progressive block loading
Variable amplitude loading	More realistic loading Less sensitive to accuracy of fatigue formulation	Higher peak loads Complicated hardware and software Can be slower

12.7 Deterministic corrections

12.7.1 Tare loads

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

Tare loads can result from the masses of

– the blade itself;
– clamping structures to connect the actuators;
– hinges at the blade;
– actuators;
– Whiffle tree apparatus;
– cables, slings, and transducers.

The masses of any of the above equipment and their location with respect to the blade co-ordinate system shall be documented. The relevant test loads shall be corrected to account for these additional mass loads. Care should be taken to establish the zero level of the load cells within a known uncertainty level.

In some cases, tare loads may act perpendicular to the sensitive axis of the load cell. For example a horizontally orientated actuator connected at one end to the test rig and at the other end to the blade will transfer part of its dead weight to the blade. This load is not measured by the load cell but should be accounted for. Some equipment (e.g. Whiffle tree components) may introduce local moments to the blade that cannot be completely eliminated.

12.7.2 Load angle changes

As the blade deflects, the load direction relative to the blade orientation can change. These load direction changes should be taken into account in evaluating the test load. This is covered in more detail in annex C.

12.7.3 Induced torsional loading

Torsional moments acting on the blade can be caused by spanwise deflections of the blade during loading. As the blade is deflected in one direction, any load or load component acting perpendicular to the first will generate a torsional moment at the root that is equal to the initial deflection times the perpendicular load. These moments can be significant and should be considered when specifying the test load.

Torsional moments can also be applied when the chordwise position of the applied force(s) is different from the elastic axis of the blade. The applied loads may be intentionally offset from the elastic axis to give a prescribed torsional moment.

12.8 Data collection

12.8.1 General

Data collection covered in this clause relates to test activities requiring monitoring and recording. These activities range from visual inspection to generating permanent records of calibrated data. The data requirements may vary because of customer requests or requirements set by standards authorities.

12.8.2 Load measurement

For strength tests, the magnitude, location and direction of the loads applied shall be monitored and recorded throughout the test. For the tests to determine blade properties described in clause 13, the applied load should also be recorded and, if applicable, data sampling frequencies should be sufficient to measure dynamic load changes within acceptable tolerances.

The applied loads can be monitored in different ways. The most appropriate method for monitoring the loads is generally dependent on the test method used. In the following, the different principles are mentioned:

– deflections;
– forces/loads;
– accelerations;
– strain gauges;
– combinations of these.

Often the load can be determined from blade displacements, particularly during fatigue tests in which the applied force is different to what it would be under static loading. The applied force is measured directly in many cases, particularly during static loading. Accelerometers and strain gauges may also be used to determine the load under some circumstances. These sensors may also be used to control the load level that must be maintained within the specified tolerances throughout the test.

A load cell should be placed between the blade and the load application device during static tests. For a Whiffle tree, it is necessary to measure loads at the top of the Whiffle tree where the single load is applied. The geometry of the Whiffle tree can be used to determine the loads at each blade attachment point.

12.8.3 Damage inspection

At frequent intervals during the test, the blade should be visually inspected for surface damage such as cracks, delamination, and debonding. Obvious surface damage should be photographed. Changes in deflections, strain levels, stiffness, damping, sound emission, creep, and modal shape may also be included in the inspection procedure. A video record of significant events occurring during the test is recommended.

12.8.4 Changes in stiffness

Stiffness changes can be used as failure criteria of the blade for static or fatigue tests (see clause 11) and provide a reliable way to monitor progressive damage during a fatigue test using any test method.

During resonance fatigue testing, the stiffness is an essential parameter to monitor because the load distribution depends on the stiffness distribution of the blade. Depending on the control philosophy, the stiffness can be monitored by deflection, strain gauge measurements, frequent calibration loadings, or a combination of these methods.

For displacement control, stiffness measurements are generally taken at slow speeds or under quasi-static load conditions. Both load and displacement should be measured. If displacement control is used, the displacement range should be periodically adjusted to maintain constant load when stiffness changes occur.

Temperature changes in the ambient conditions can also cause variations in the blade stiffness that are not due to damage from loading. Some heating of the structure due to non-elastic flexure of the material may occur. Generally, this is not a problem at common test frequencies. During high-frequency tests, the generation of heat in the blade should be monitored and controlled. Normally, large temperature gradients on the blade that can be easily detected by touch may indicate an internal or subsurface failure in progress. Smaller thermal gradients are normal and will not substantially affect the test.

12.8.5 Strain monitoring

Changes in the blade condition that are not detectable by visual inspection can often be found by the use of strain gauges. Strain gauges placed in a grid pattern and spaced over the tested region may detect internal failures that might otherwise go unnoticed by showing a corresponding redistribution in the strain patterns over the blade's surface. Alternatively, critical areas and areas of high stress, identified by the blade structural design analysis, can be instrumented using strain gauges. Strain magnitude shifts can be used to infer localized internal failures. This might be used in the selection of the specific additional tests that might be performed after completion of the primary fatigue testing. Strain gauges may also be used to measure blade properties but this topic is covered in clause 13.

12.8.6 Environmental conditions monitoring

The temperature and humidity in the laboratory should be recorded at intervals sufficient to monitor ambient fluctuations during the test. These measurements may not be sufficient to establish the true moisture condition of the blade at any given time. It may take several weeks at constant humidity for a blade to reach an equilibrium state. Therefore, it may be necessary to section the blade and test for moisture content after the test is over.

Similarly it takes several hours for a blade to reach an equilibrium temperature. Efforts should be made to minimize temperature fluctuations by eliminating thermal draughts and local heating sources. The test blade should be brought into the laboratory environment well in advance of the test. If ambient temperature cannot be stabilized over time, more frequent measurements should be made. If different ambient conditions exist over the blade surface, multiple measurements on the test blade should be made.

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

Specialized test environments may be specifically requested. In such cases, additional instrumentation may be required.

12.8.7 Failure description

Failure modes should be described and recorded in accordance with the failure criteria mentioned in clause 11. At the end of a test it is reasonable to section the blade at the failure location to investigate the mode of failure.

13 Other tests determining blade properties

13.1 General

In the previous clauses, only strength-related tests are dealt with. However, other tests giving additional information on other structural or dynamic properties are important and are also commonly carried out. These tests can be performed independently of the strength tests, but normally, for practical reasons, most of them will be performed in connection with the strength tests – especially with the static strength test. If required other supplementary tests, such as non-destructive tests can be carried out. These tests will only be mentioned briefly. For some of these tests the deterministic corrections (see 12.7) will be applicable as well.

13.2 Test stand deflections

The measured displacement and stiffness 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.

13.3 Deflection

Normally flatwise deflections have most significance because of limited clearance to the wind turbine tower. During the test, deflections of the blade and test rig should be recorded. The test will often be done in combination with the static strength test.

13.4 Stiffness distribution

The blade bending stiffness in given load directions can be derived from the load/strain measurements or from deflection measurements.

The load/strain method is very suitable if a detailed stiffness distribution is required – especially in the root and inner part sections. The strain measurement points have to be chosen carefully and sets of strain gauges – one on each side of the blade at the same spanwise positions – are to be distributed along the blade. By loading the blade tip and measuring the strains on each side of the blade and knowing the distance between the gauges, the local curvature can be calculated. From the curvature and the bending moment the stiffness can be derived. Care has to be taken that the gauges are placed in "undisturbed" areas of the skin.

Blade displacements should be measured at spanwise positions along the blade length for the specified loads. The number of displacement measurement locations should be adequate to determine the displacement curve and stiffness for the whole blade.

The displacement method is in a way a simpler and quicker test, but the deflections have to be corrected for the deformation of the blade root fixture. Further, the resolution is limited on the inner part of the blade using this method and some smoothing is necessary, giving a high degree of uncertainty of the result.

The torsional stiffness of the blade can be expressed in terms of angular rotation as a function of increasing torque.

13.5 Strain distribution measurements

If requested, the strain distribution can be measured by strain gauges placed in areas of interest giving the strain level distribution for the blade. The gauge location and orientation should be documented. The number of measurements is dependent on the blade being tested (e.g. size, complexity, areas of interest). If non-linearities are required to be captured from zero stress level, the gauges might have to be referenced with an unloaded blade with compensation for the tare loads (see 12.7.1).

Blade strains should be measured at critical areas on the blade skin, typically at blade locations in which geometry transitions and critical design details are present or the strain level is expected to be high. Some recommended measurement locations are:

– root to hub connection;
– blade root;
– root to blade transition;
– large section changes;
– material or thickness changes;
– aerodynamic brake mechanism transition zone;
– design details and joints;
– internal joints, stiffeners and beams.

Each measurement point can include up to three strain measurements. If the direction of the principal strains is not known, a strain gauge rosette can be used to determine the magnitude and direction of the principal strain values at the measurement points.

The use and calibration of strain gauges will not be described here – it should be known by the test laboratories.

If only stress concentrations or a certain strain level are of interest, a stress coat can be used. This is a strain-sensitive brittle lacquer with a well-defined cracking limit. After each load step, the coat has to be inspected for cracks. Stress coat is to be used according to the manual.

Stresses can also be derived from photo-elastic measurements [3].

13.6 Natural frequencies

Normally, the important frequencies are limited to the first and the second flatwise and the first edgewise frequencies (and in some cases the first torsional frequency). For most blades, these frequencies are well separated and more or less uncoupled. Consequently, they can be measured directly one by one by putting the blade into the desired vibration mode while monitoring signals from (for example) strain gauges, displacement transducers, or accelerometers representing the vibration mode. Exciting the second flatwise mode can cause some problems – especially for very stiff blades.

If it is not possible to excite the modes separately, a frequency analysis can be made on signals generated by exciting the blade in free vibration outside its harmonics [14].

13.7 Damping

The structural damping can be recorded for the flatwise and edgewise directions by measuring the logarithmic decrement of an undisturbed oscillation. The amplitude of the oscillation has to be small to avoid influence from aerodynamic damping (a few centimetres). It should be borne in mind that the damping is normally very dependent on the temperature.

13.8 Mode shapes

It can be shown that the normal mode shape values, related to lightly damped linear structures with well-separated natural frequencies, can be approximated by the imaginary part of the transfer function (at resonance) relating the force input to the acceleration response at the points where the mode shape values are to be determined.

Flatwise and edgewise measurements can be performed by applying an excitation (at the frequency of concern) at an appropriate point (mostly the tip) of the blade while it is mounted on a rigid test stand. The resulting acceleration responses, from positions spaced with suitable resolution along the blade, has to be monitored. The exciting force can be measured by a force transducer and the accelerations by accelerometers. The measurements can then be fed into an analyzer that offers the possibility of extracting the modulus as well as the phase of the complex transfer function at the resonance frequency. A detailed description is given in [7].

Instead of moving a single accelerometer, the mode shapes can be derived by driving the blade with a range of forcing frequencies, with a number of accelerometers well-distributed along the blade [11].

13.9 Mass distribution

A rough mass distribution is given by the total mass of the blade and the centre of gravity. A more refined method is described in bibliographic reference [8]. If necessary, the mass distribution can be measured by cutting the blade into small sections and weighing each of those.

13.10 Creep

For materials sensitive to creep it may be necessary to do a test to define the creep and recovery characteristics for the blade. These tests are performed for a longer time duration under static loading of the blade (e.g. hours or days). During the test, the deflection should be measured frequently and the deflection versus time should be recorded. After a period of time, the load is removed and the recovery versus time should be recorded as the blade relaxes.

13.11 Other non-destructive testing

Non-destructive testing (NDT) techniques can, in some cases, be used to check that the blade is built in accordance with the design assumptions and to find manufacturing defects. NDT can be performed in connection with other tests. Some of the methods used are:

- measurements checking the geometry of the blade (e.g. dimensions, profile, etc.);
- coin-tap;
- acoustic transmission;
- ultrasonic testing;
- acoustic emission [9];
- thermal imaging [10].

13.12 Blade sectioning

Blade sectioning can be used to check that the blade is built in accordance with the design assumptions and to find manufacturing defects.

The following properties can be checked:

- the mass distribution of the blade;
- the (e.g. aerofoil) geometry;
- the build-up of laminates, beams, glued connections, etc. (e.g. finding glass content, fibre orientation, porosities in a fibreglass blade).

Blade sectioning can also be required to investigate the failure modes.

14 Reporting

14.1 General

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

14.2 Content

The test report should include the following items, depending on the type of test.

14.2.1 General – for all tests

The following information is to be given:

- table of contents;
- contractor for the test;
- date and location for the test;
- objectives;
- blade data;
- blade identification;
- summary of tests and test results;
- appendices: drawings, measured data, logbook, photographs, etc.

14.2.2 Static tests and fatigue tests

The following information is to be given:

- description and derivation of test load;
- description of failure criteria;
- experimental set-up and procedures;

- test equipment used;
- calibration of measurement equipment;
- locations of strain gauges and points for measuring deflections (drawing);
- measured deflections, loads and load directions;
- accuracy of test results;
- evaluation of test loads including test load distribution [9];
- description of failures [10];
- measured levels and ranges of strains, loads;
- load directions;
- summary of loads and deflections throughout the test.

14.2.3 Other tests

The format and content of a report concerning other tests on a blade will generally follow that described above.

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[9] For design load-envelope testing only.

[10] It is also required that all failures on the blade are reported and documented even though it is decided that they are irrelevant for the result.

Annex A
(normative)

Partial safety factors considerations

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 (see 9.2).

It appears that the product of the partial safety factors (γ_m, γ_n and γ_f) is similar in magnitude for many design standards [1]. However, some standards allocate more of the overall safety to one or other of these factors. This even to the extent that in some standards the partial safety factors on loads are unity while in others partial safety factors on materials are unity. It seems that in the codes the total uncertainty is sometimes (for whatever reasons) concentrated in one or two of the above-mentioned factors. For the design, this makes no difference because all have to be applied. However, in testing, this makes a difference because only γ_f and γ_n will affect the test load (see 9.2).

As a consequence, applying different design codes can result in the same design but in a different and possibly underestimated test load. To address this possibility, the following minimum values for the product are considered reasonable, based on previous experience:

for static tests: $\gamma_{fu} \times \gamma_{nu} \geq 1,25$

for fatigue tests: $\gamma_{ff} \times \gamma_{nf} \geq 1,15$

If the design process, or the standard with which the design complies, gives higher overall partial safety factors, the above minimum values will have no effect on the test loads. However, if a design standard puts all or most of the partial safety factor onto either the loads or the consequences of failure or the materials, then these minimum values will help ensure a reasonable minimum value of test load that is not as dependent on where the factor is allocated.

As an example, consider the following comparison between the first and second editions of IEC 61400-1 for fatigue when the minimum is not applied.

	61400-1 Ed. 1	**61400-1 Ed. 2**
Partial factors		
γ_{mf}	1,25	1,10
γ_{nf}	1,0	1,15
γ_{ff}	1,0	1,0
Product of partial factors affecting the **design** ($\gamma_{mf} \times \gamma_{nf} \times \gamma_{ff}$)	**1,25**	**1,26**
Product of partial factors affecting the **test load** ($\gamma_{nf} \times \gamma_{ff}$)	**1**	**1,15**

As may be seen, for essentially the same factor used in the design, the factor used in the test is quite different depending on the allocation of the safety between γ_f and γ_n. In the ideal case, tests under different codes should lead to the same test loading and results. The cited minimum values are provided to limit the effects illustrated above.

Annex B
(normative)

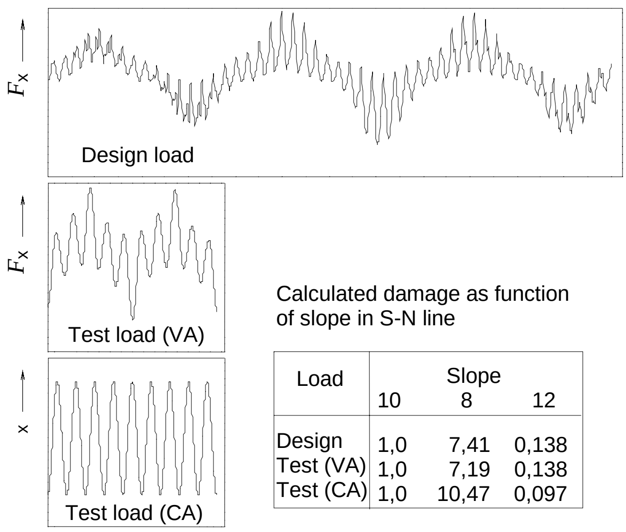
Sensitivity of the evaluation to fatigue formulation

Because the design load is very different from the test load, the comparison of the damage accumulation from the design load and the test loading will depend on the fatigue formulation used. An accurate knowledge of the fatigue behaviour given by the true fatigue formulation will result in an accurate comparison. Normally however, the true fatigue formulation is not exactly known. The accuracy depends on the knowledge for the particular material.

Usually the fatigue formulation is given by an S-N curve, Goodman relation, Miner summation, counting procedure, factors for others influences, etc. Uncertainties in the prediction of the fatigue damage are related to the uncertainties in:

– the slope of the S-N curve;
– the Goodman diagram;
– the validity of the Miner summation;
– the applicability of the cycle counting procedure;
– the effects of other influencing factors.

The error in the prediction of the fatigue damage due to these uncertainties will be different for the design load and the test load. As a result, these uncertainties or errors will affect the comparison of the severity of the test load with respect to the design load.



Load	Slope 10	8	12
Design	1,0	7,41	0,138
Test (VA)	1,0	7,19	0,138
Test (CA)	1,0	10,47	0,097

IEC 429/01

Figure B.1 – Comparison of sensitivity for constant amplitude (CA) and variable amplitude (VA) loading on the fatigue formulation

For instance, changing the slope of the S-N curve may result in a different conclusion about the severity of the test load with respect to the design load. The sensitivity to the fatigue formulation will be greater the more the spectrum of the test load differs from the design load. For this reason, the conclusion regarding the severity of the test loading with respect to the design loading will be more sensitive to the fatigue formulation in case of a constant amplitude test loading than in case of a variable amplitude loading with a similar spectrum and sequence.

This is illustrated in figure B.1 which shows the fatigue damage for a design load and two possible test loads. The fatigue damage values are given using different slopes of the S-N curve. Assuming a slope of the S-N curve of 10, the variable amplitude and the constant amplitude loading have the same damage (being 1,0) as the design load. In this case, both test loads have the same severity as the design load. If the actual slope of the material is 8 instead of 10, the fatigue damage for all loads changes. However, the VA test load still has the same severity as the design load (both close to 7,3) whereas the CA loading appears to be more severe by a factor of 1,4 (10,47 divided by 7,3). If the actual slope is 12 instead of 10 the CA test load is less severe than the design load, again by a factor of 1,4 (0,138 divided by 0,097) whereas the VA test load has the same damage as the design load. The factor of 1,4 in life is equivalent to 4 % on the basis of stresses or load.

Other possible errors in the conclusion regarding the severity of the test load result from the fact that the fatigue damage for variable amplitude loading seems to be inaccurately predicted for GRP material by the current fatigue formulations. This is demonstrated by recent high cycle variable amplitude (WHISPER) fatigue tests on GRP coupons [12]. It appears that the predicted fatigue life in the case of variable amplitude will be underestimated using the current fatigue formulations using a very accurate S-N curve based on constant amplitude tests. This underestimation depends on the stress level but can be on the order of a factor of 100. On the basis of stresses of loads, the difference would be a factor of about 1,5.

Both examples illustrate the fact that the conclusion as to the severity of the test load is dependent on the accuracy of the fatigue formulation applied. It can also be concluded that the sensitivity increases the more the test load differs from the design load. For this reason, the sensitivity increases as the test load approaches a CA load. For the same reason, the sensitivity also increases with the reduction in the number of cycles applied during a test load.

Annex C
(normative)

Loading angle change considerations

For both static and fatigue testing, blade deflections can cause significant load angle changes that can alter the intended loading. There are several influences which should be taken into account. When a load is applied to a blade, the corresponding deflection alters the blade geometry by deforming it, which changes the orientation of the load. The problem may arise under various circumstances.

Under fatigue or static loading, the projected length of the bent blade with respect to the horizontal plane becomes shorter. For small deflections in the load direction, this effect can usually be ignored, but for larger displacements or displacements perpendicular to the load direction, a significant reduction in the applied blade moment can be induced. If the load point is fixed on both the blade and the corresponding reaction point (e.g. as with hydraulic actuators), the force in the load direction will not remain normal to the blade. As a result, the moments along the blade will be reduced. If the load point can be adjusted at one end (e.g. as with a crane under static loading), the force application can usually be maintained in a normal direction but the moment-arm is usually reduced, which in turn reduces the moments. In either case, the force should be increased to arrive at the same moment distribution.

Under multi-axial loading, where some displacements are in the direction perpendicular to the load, a more substantial correction may be necessary. During a fatigue test for example, flatwise deflections move the lead-lag load application point perpendicular to the lead-lag load direction. Even relatively small deflections can have a large effect on the intended loading. These flatwise deflections may have the unintended effect of raising the flatwise loads while decreasing the lead-lag loads, because a component of lead-lag force is transmitted in the flatwise direction. The same effect can happen in reverse, where higher lead-lag loads can be induced by the flatwise actuator. These induced load errors can be minimized by using long actuators or linkages relative to the magnitude of the perpendicular displacements. Since flatwise displacements are typically higher, this generally means the lead-lag actuator must be longer than is needed for simply achieving the necessary deflections. The remaining errors may be compensated for by altering the test loading appropriately to account for the expected geometry changes. Better control schemes may also be available to program blade defections precisely to eliminate the undesired effect.

Another error can be induced during high blade deflections when rigid load saddles are used. As described, the load saddle is usually a block of wood which encloses the blade's cross-section at the desired load point. The load is applied to the edge of the saddle and the load is transferred through the saddle to the blade. When the deflection is high the load saddle is at an angle to the load direction, and the blade reaction force creates a force couple that tends to either increase or decrease the intended moment depending on how the load is applied. This effect is shown in figure C.1. This effect can be significant and should be minimized by saddle designs which self-compensate by keeping the load's line of action passing through the desired blade chord.

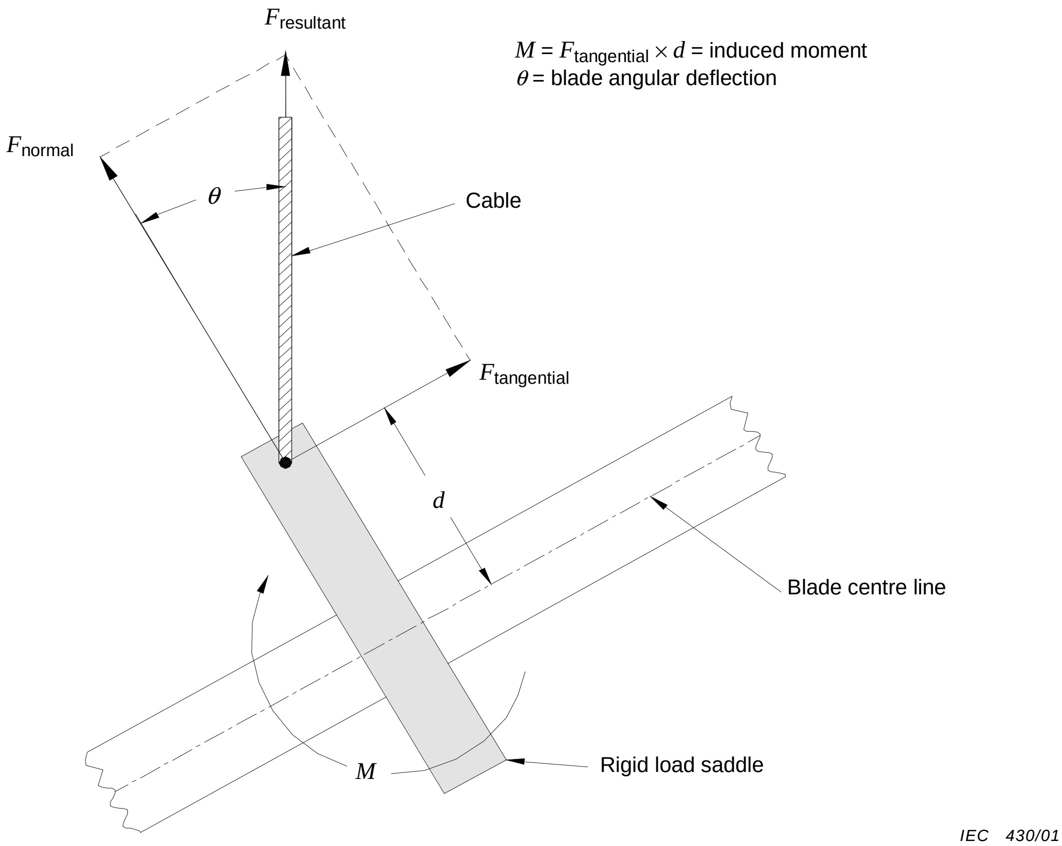


Figure C.1 – Force couple introduced bending moment during static testing

The consequences of significant load angle changes are usually to alter the moment distribution in a way which may prevent the intended distribution from being achieved. In these cases, it is best to anticipate the deflections and compensate for them with the test hardware. Generally, it is most important to correct the forces for load angle deflections in the maximum load case. Therefore, the intended loading should be developed with the blade already deflected. The effects of high blade deflections can be reduced if the undeflected blade axis is tilted from the horizontal in a direction opposite the load direction. This will increase the deflection range for which adjustments are not necessary. Tilt capability can be built into the test stand or added as part of the test fixture. For blade tests with high deflections, it may be necessary to measure more parameters than with stiffer blades. Blade angular displacements, load angles, load radial position, and linear blade displacements may all be important.

High blade deflections give rise to particular problems whilst testing in the vertical plane. These can be eliminated by loading the blade horizontally. High blade deflections in three planes can be measured remotely using land surveying techniques. Changes in the angle of the applied load, as the blade deflects, can be monitored by inclusion of a displacement transducer within the test set-up [13].

Annex D
(informative)

Examples of test set-ups

D.1 Hydraulic actuators

Hydraulic actuators are commonly used to apply fatigue loads. The actuator is mounted between a rigid support or floor and the blade attachment fixture. Actuators can be controlled by monitoring load or displacement.

Hydraulic actuators allow a wide variety of test conditions and control options. Test frequency, load amplitude and sequence, load distribution, and the number of load axes can be varied. Actuators can be used at a single point or in multiple combinations. Multiple actuators are used to apply multi-axial loading. Two actuators at two different spanwise locations can be used to apply a distributed fatigue load to the blade. A single actuator may be used to apply combined loading of the flatwise and edgewise loads, as described in 12.5.1.5, and the resultant load should be applied to the blade at the proper angle. Loads can be applied at either constant or variable amplitudes depending on the hydraulic control system used.

The principal disadvantage of hydraulic actuators is in the cost. Also, while most types of loading are possible, large displacements, high frequencies, or multiple spanwise load points require expensive specialized equipment and generally large volume hydraulic pumps.

The hydraulic actuator test set-up may vary depending on the test requirements and the blade properties. Most hydraulic actuator test systems use servo-hydraulic feedback systems to control the applied load. A command signal is sent to the servo-valve and the intended response is monitored by the controller. Actuators may be controlled using displacement or load criteria. Adjustments are made to keep the load or displacement signal within pre-established limits. Many factors can affect the accuracy and stability of the test.

IEC 431/01

Figure D.1 – Example of single-axial test set-up using a hydraulic actuator (NREL, USA)

IEC 432/01

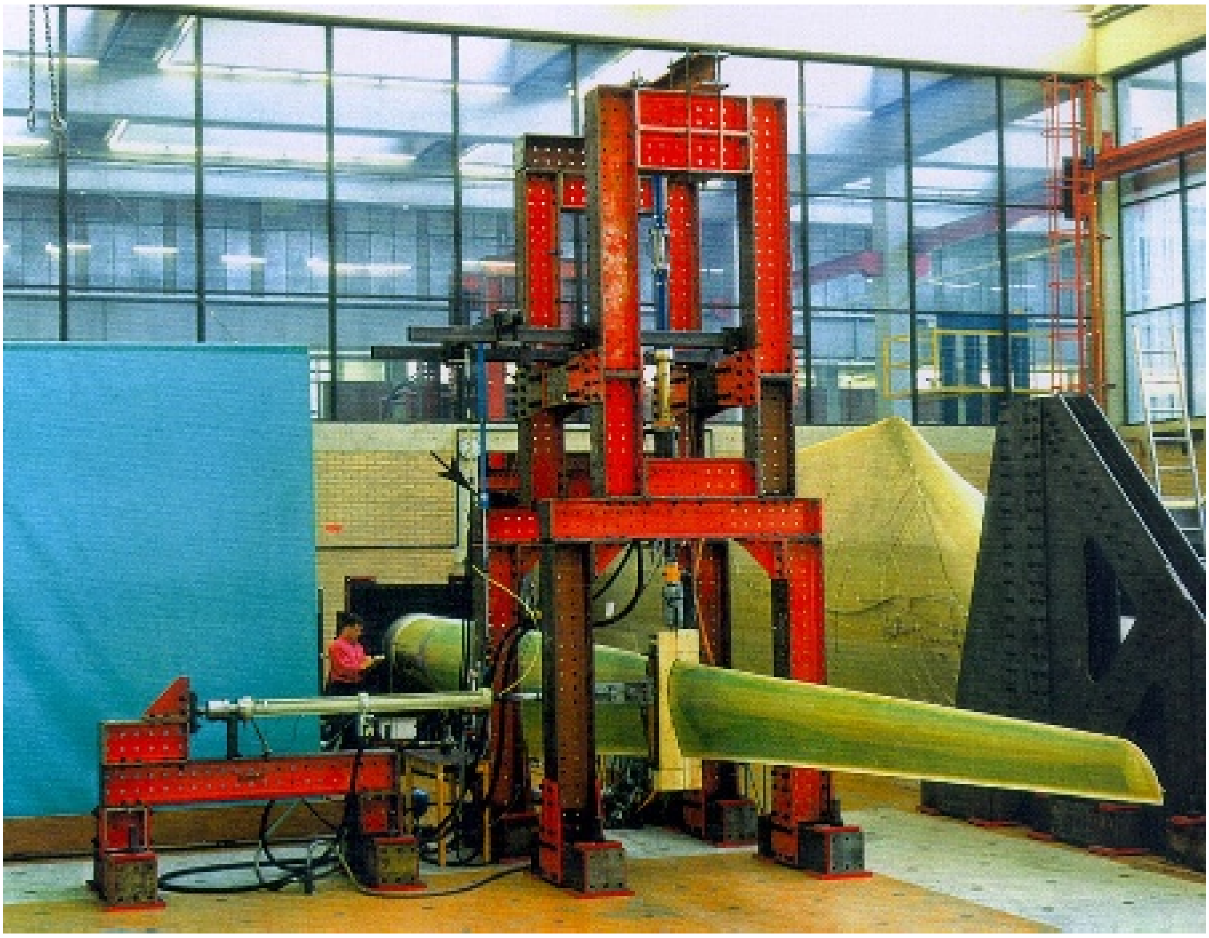
Figure D.2 – Example of single-axial multiple-point test set-up using hydraulic actuators (CRES, Greece)

Hydraulic actuators should be fatigue-rated to endure many millions of load cycles between rebuild or maintenance intervals. Actuators must be equipped with durable load and displacement transducers as integral components. Actuators can be single-ended or double-ended. Double-ended actuators may be more stable for reversing load applications or for long displacements. Double-ended actuators are more durable and will last longer, but they are longer and heavier than single-ended actuators for the same displacement and load capacity. Many actuators with different load and stroke capacities may be required to accommodate various loading requirements. Anti-backlash attachments must be provided at the actuator ends to protect the components if reversing loads are used.

Large hydraulic accumulators and check valves may be necessary to smooth pressure fluctuations in both the pressure and return lines. A large hydraulic pump is necessary to provide high pressure hydraulic fluid to the actuators. A precision servo-valve is recommended for controlling the flow of oil to the actuator. Hydraulic oil must usually be cooled. It may be necessary to monitor the oil temperature if the displacement sensors are immersed in the hydraulic oil as temperature changes may cause the sensor to drift.

The interaction of the hydraulics with the test article can lead to hydraulic resonance or undesired dynamic system interactions. The correct combination of servo-valve capacity, actuator load and displacement capacity, accumulation capacity and pressure on both the pressure and return lines, and flow rate must be achieved for optimum dynamic stability. Each test set-up may require significant hardware adjustments. External parameters that may affect test stability are blade natural frequencies, blade mass and stiffness, and test load and speed requirements. Test frequency is limited by the maximum hydraulic oil flow rate that can be delivered. The amount of oil required will increase with actuator stroke and load capacity, and the number of actuators.

For optimum accuracy, feedback control from the displacement or load sensors on the actuators is required. Auxiliary feedback sensors,(e.g. accelerometers, line pressure sensors) may be required in some instances to control hydraulic resonances or higher order blade natural frequencies.



IEC 433/01

Figure D.3 – Example of multi-axial test set-up using hydraulic actuators (Stevin Lab, Delft University)

D.2 Eccentric rotating mass

D.2.1 General

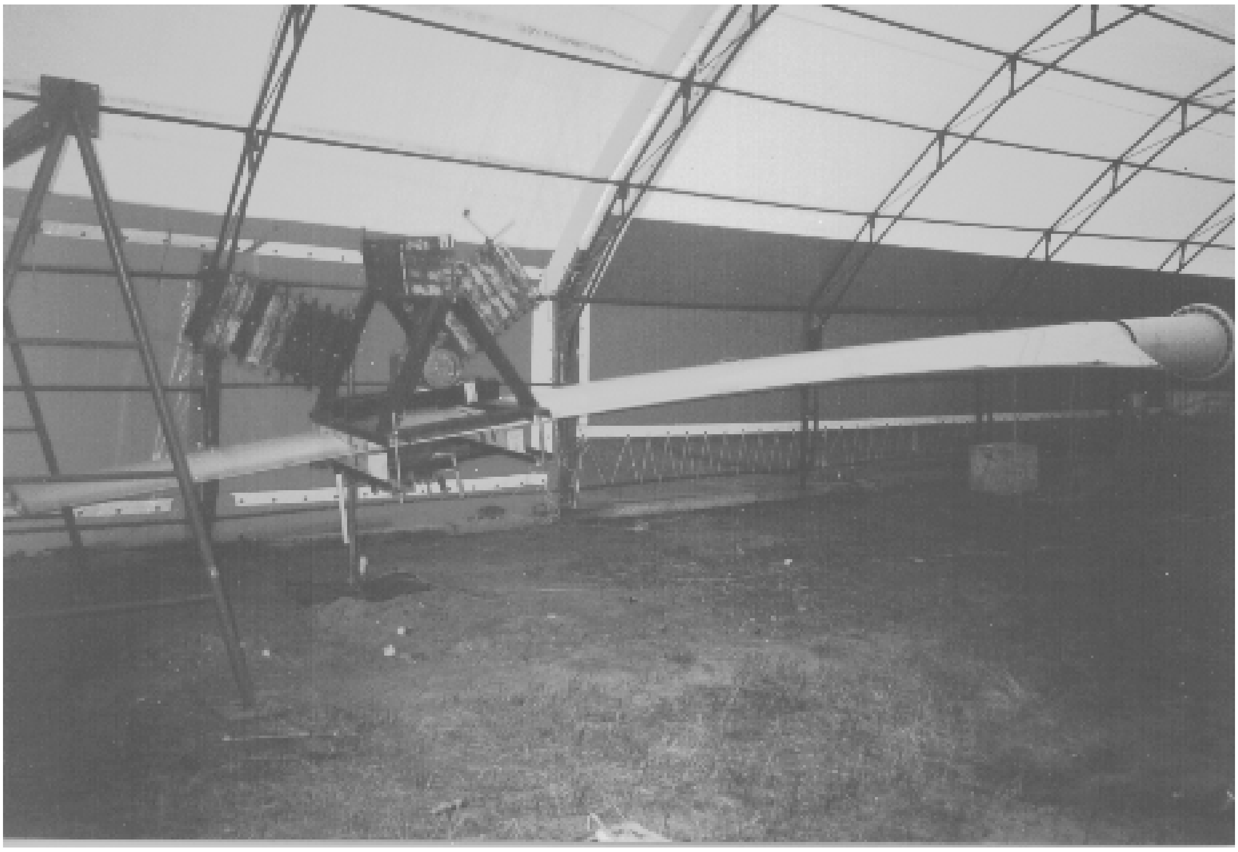
The principle of the eccentric rotating mass test method is to excite the rotor blade at a frequency close to the natural frequency of the rotor blade. A variable speed exciter unit with an eccentric rotating mass is tuned to the oscillating frequency that gives the desired response. The task of the exciter unit is to maintain the energy in the oscillation, resulting in a test with stable constant amplitude load cycles.

In eccentric mass testing, the spanwise load distribution follows the 1st modal shape of the tested system (blade including the dead weight of the pre-load and exciter). The R-ratio of the test load is adjusted by applying a pre-load to the blade at the exciter location.

The advantages of this test method are that the test set-up is simple and stable and the test is inexpensive. The disadvantages are that this method is limited to a constant amplitude or block loading and the test frequency is limited to the natural frequency of the tested system (blade including pre-load).

D.2.2 Test set-up

The typical set-up for a flatwise test has the blade root fixed to a test rig, and the tip chord of the blade in a horizontal position with the downwind side of the blade facing towards the ground. The exciter and the dead weight are positioned to give the desired load distribution in the tested areas of the blade. For example, if the root section and the inboard blade sections are defined as the tested areas, the load can be established by mounting the pre-load and the exciter on the outer part of the blade (e.g., at 75 % of the blade length). The weight of the pre-load, which includes the exciter, is usually a little less than half of the weight of the intended test loads in the root area. It may be possible to modify the load distribution to achieve the desired loading by placing pre-loads at different spanwise locations on the blade.



IEC 434/01

Figure D.4 – Example of test set-up using an eccentric rotating mass (Risø, Denmark)

After starting the test, the blade loading has to be compared with the intended loading in the areas of interest. Care must be taken to make sure that areas outside of the test region are not seriously overloaded.

The method for an edgewise test is similar to the flatwise test mentioned above, but usually the blade is fixed with the tip chord line in a vertical position. A combined edgewise and flatwise test can be made by setting up the edgewise test, mentioned above, and pre-loading the blade in the flatwise direction by means of a stay. Another possibility is to set up the test with two exciters mounted perpendicular to each other.

D.2.3 Establishing loading

The change in modal shape because of the dead weight of the pre-load and exciter will, when the test is running, cause a change in the load distribution on the blade compared with the distribution given by the static test. Therefore, it has to be taken into account when selecting the areas to be tested and the number of cycles for the test.

For excitation of the blade, a speed controllable motor with an eccentric rotating mass can be used. To obtain the desired R-ratio, a dead weight has to be applied to the blade giving the mean value of the load spectrum. The eccentric rotating mass and its frequency is to be adjusted to give the blade the desired displacement, which can be derived from the calibration test.

The requirements for control and data acquisition equipment will be determined to a large extent by the chosen control and monitoring philosophy.

D.2.4 Test control issues

D.2.4.1 Amplitude adjustment

By adjusting the exciter in a frequency range just below the natural frequency of the blade (including the dead weight), the amplitude of displacements can be tuned to the desired levels.

D.2.4.2 Change in stiffness

Depending on the control philosophy, the stiffness can be monitored either by the deflection, by strain gauge measurements, by frequent load calibrations, or by a combination of these methods.

D.2.4.3 Displacement control / stroke limitation

The load level must be maintained within the specified tolerances throughout the test. As the blade behaviour is usually linear elastic, the load level can be derived from the displacement. The displacement can be monitored either directly by displacement transducers or indirectly by measured accelerations (or under special circumstances by strain gauge measurements).

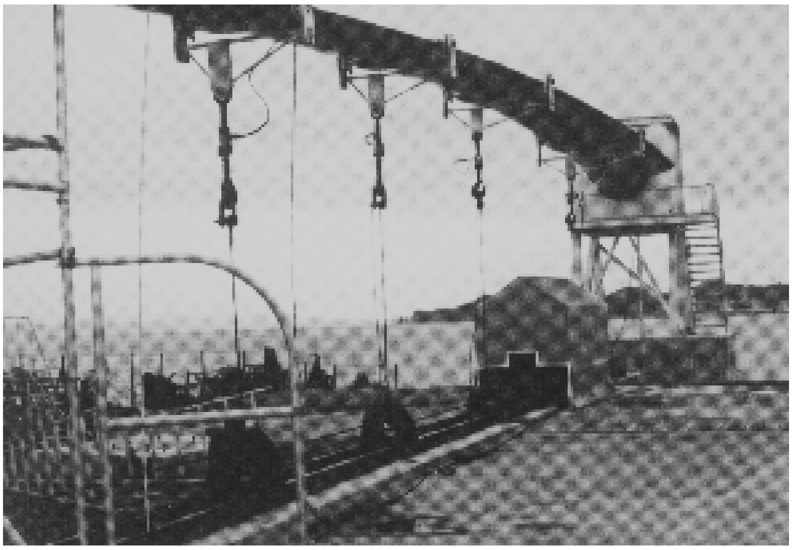
It is advisable to have an emergency switch to stop the test if a certain load limit is exceeded.

D.2.4.4 Temperature

Large changes in the ambient temperature may cause changes in the blade stiffness and in the mean deflection of the blade, which may require adjustments to the test.

D.3 Other loading devices

Cranes or hoists work best when displacements are large, and when test conditions require the load to be applied from overhead. For very stiff structures it may be difficult to control the rate of load application unless the crane is equipped with slow speed controls. Winches are used in a similar way, but can be mounted on any rigid support.



IEC 435/01

Figure D.5 – Test set-up using winches for static loading (Japan).

Sandbags can be difficult to handle and extreme caution is advised in adding bags to the blade at extreme loads. To safely accomplish this, the blade is supported underneath while additional weight is added to avoid a failure while the load is being changed. Sandbags may be placed along the blade manually or using automated equipment. It may be necessary to install fixtures along the blade span to prevent axial slippage of weights as the blade deflects. Sandbags may be difficult or impossible to use with more flexible blades due to angle change. It may also be difficult to apply edgewise loads using this method.

IEC 436/01

Figure D.6 – Test set-up using sandbags and lead ingots (City Un., UK).

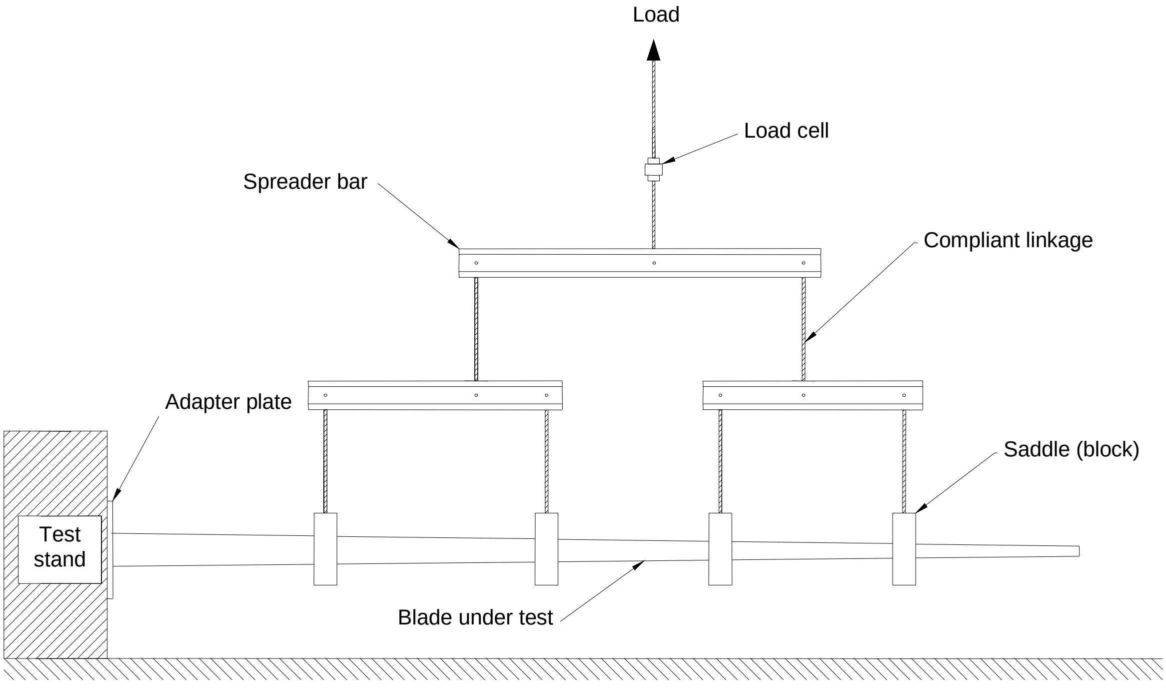
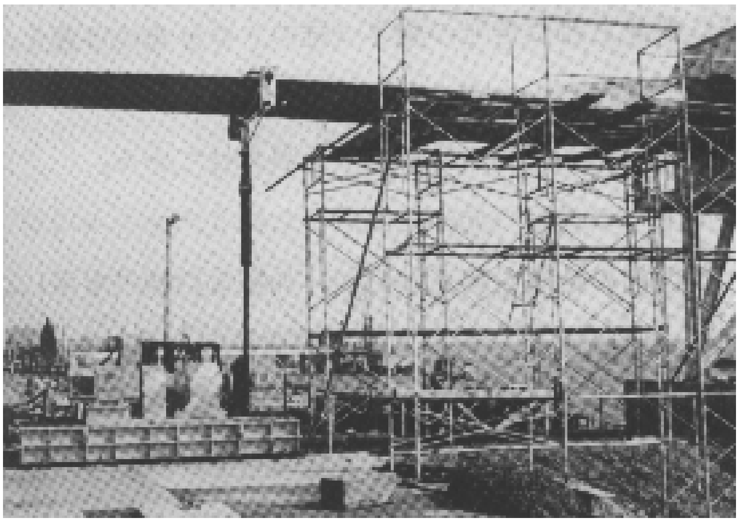


Figure D.7 – Example of a Whiffle tree

Whiffle trees are used to apply distributed point loading to a blade under static loading. Figure D.7 shows a schematic of a typical Whiffle tree. All linkages and connections are compliant to prevent the load fixture from altering the blade stiffness. The Whiffle tree geometry is designed to apply loads to the blade that approximate the distribution of the target test load. With larger blades, it may be practical to test the blade in sections. For example, one Whiffle tree may be used to test the tip of the blade and another for the inboard region. When a Whiffle tree is used, it is usually easier to pull up on the blade using a crane but it may also be possible to use hydraulic actuators. Generally, Whiffle trees should be constructed from lightweight materials.

Rocker arms and levers, and pulleys and cables, can be used to alter mechanical advantage by multiplying either load or displacement for a particular loading device.

Cyclic loading can be applied to wind turbine blades by attaching the blade to a push rod connected to a rotating camshaft. The linear motion of the push rod can be adjusted to give the desired deflection. This method is generally limited to displacement control and to constant amplitude loading in a single direction. The displacements can be fixed by the hardware using a rigid link or more compliant links can be used to supply system damping. If the link is rigid, no additional displacement signal is necessary because displacements are controlled by the geometry of the system.



IEC 438/01

Figure D.8 – Example of test set-up using a camshaft system with a visco-elastic shaft for fatigue loading (Japan).

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Egne notater/Notes: