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**Wind energy generation systems –
Part 8: Design of wind turbine structural components**

**Systèmes de génération d'énergie éolienne –
Partie 8: Conception des composants structurels des éoliennes**



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WIND ENERGY GENERATION SYSTEMS –

Part 8: Design of wind turbine structural components

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Draft	Report on voting
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Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this International Standard is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

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INTRODUCTION

This part of the IEC 61400 series outlines the minimum requirements for the design of wind turbine nacelle-based structures and is not intended for use as a complete design specification or instruction manual.

Several different groups can be responsible for undertaking the various elements of the design, manufacture, assembly, installation and maintenance of a wind turbine nacelle and for ensuring that the requirements of this document are met. The division of responsibilities between these parties is a contractual matter and is outside the scope of this document.

The requirements stated in this document may be altered if it can be sufficiently demonstrated that the structural integrity of the system is not compromised.

The specific scope of the document is provided in Clause 1. For cases out of the scope of this document, reference should be made to relevant IEC/ISO standards.

WIND ENERGY GENERATION SYSTEMS –

Part 8: Design of wind turbine structural components

1 Scope

This part of IEC 61400 outlines the minimum requirements for the design of wind turbine nacelle-based structures and is not intended for use as a complete design specification or instruction manual. This document focuses on the structural integrity of the structural components constituted within and in the vicinity of the nacelle, including the hub, mainframe, main shaft, associated structures of direct-drives, gearbox structures, yaw structural connection, nacelle enclosure. It also addresses connections of the structural components to control and protection mechanisms, as well as structural connections of electrical units and other mechanical systems. This document focuses primarily on ferrous material-based nacelle structures but can apply to other materials also as appropriate. The design of bolted and welded joints in the nacelle structures is included, as well as cast and forged components. Material testing requirements to use in the design process for nacelle structures are specified. While the structural connections of the gearbox and the main shaft are in the scope, the design of the gears and bearings are not included.

The safety level of the wind turbine designed according to this document shall be at or exceed the level inherent in IEC 61400-1:2019. Probabilistic methods to calibrate partial safety factors and for use in the design process are provided.

2 Normative references

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

IEC 61400-1:2019, *Wind energy generation systems – Part 1: Design requirements*

IEC 61400-3-1:2019, *Wind energy generation systems – Part 3: Design requirements for fixed offshore wind turbines*

IEC TS 61400-3-2:2019, *Wind energy generation systems – Part 3-2: Design requirements for floating offshore wind turbines*

IEC 61400-5:2020, *Wind energy generation systems – Part 5: Wind turbine blades*

IEC 61400-6:2020, *Wind energy generation systems – Part 6: Tower and foundation design requirements*

IEC 61400-13:2015, *Wind turbines – Part 13: Measurement of mechanical loads*

ISO/IEC 17025:2017, *General requirements for the competence of testing and calibration laboratories*

ISO 148-1:2016, *Metallic materials – Charpy pendulum impact test – Part 1: Test method*

ISO 945-1:2019, *Microstructure of cast irons – Part 1: Graphite classification by visual analysis*

ISO 1083:2018, *Spheroidal graphite cast irons – Classification*

ISO 1099:2017, *Metallic materials – Fatigue testing – Axial force-controlled method*

ISO 1143:2021, *Metallic materials – Rotating bar bending fatigue testing*

ISO 2394:2015, *General principles on reliability for structures*

ISO 3800:1993, *Threaded fasteners – Axial load fatigue testing – Test methods and evaluation of results*

ISO 6892-1:2019, *Metallic materials – Tensile testing – Part 1: Method of test at room temperature*

ISO 7500-1:2018, *Metallic materials – Calibration and verification of static uniaxial testing machines – Part 1: Tension/compression testing machines – Calibration and verification of the force-measuring system*

ISO 12107:2012, *Metallic materials – Fatigue testing – Statistical planning and analysis of data*

ISO 12108:2018, *Metallic materials – Fatigue testing – Fatigue crack growth method*

ISO 12135:2021, *Metallic materials – Unified method of test for the determination of quasistatic fracture toughness*

ISO/TR 14345:2012, *Fatigue – Fatigue testing of welded components – Guidance*

ISO 16269-6:2014, *Statistical interpretation of data – Part 6: Determination of statistical tolerance intervals*

ASTM-E466-21:2021, *Standard Practice for Conducting Force Controlled Constant Amplitude Axial Fatigue Tests of Metallic Materials*

BS 7910:2013, *Guide to methods for assessing the acceptability of flaws in metallic structures*

CEN/TS 16415:2013, *Personal fall protection equipment – Anchor devices – Recommendations for anchor devices for use by more than one person simultaneously*

EN 1090-2:2018, *Execution of steel structures and aluminium structures – Part 2: Technical requirements for steel structures*

EN 1090-3:2019, *Execution of steel structures and aluminium structures – Part 3: Technical requirements for aluminium structures*

EN 1369:2012, *Founding – Magnetic particle testing*

EN 1369:1996, *Founding – Magnetic particle inspection*

EN 1371-1:2011, *Founding – Liquid penetrant testing – Part 1: Sand, gravity die and low pressure die castings*

EN 1371-1:1997, *Founding – Liquid penetrant inspection – Part 1: Sand, gravity die and low pressure die castings*

EN 1993-1-8:2007, *Eurocode 3: Design of steel structures – Part 1-8: Design of joints*

EN 1993-1-9:2007, *Eurocode 3: Design of steel structures – Part 1-9: Fatigue*

EN 1993-1-10:2007, *Eurocode 3: Design of steel structures – Part 1-10: Material toughness and through-thickness properties*

EN 1999-1-1:2008, *Eurocode 9: Design of aluminium structures – Part 1-1: General structural rule*

EN 1999-1-3:2007, *Eurocode 9: Design of aluminium structures – Part 1-3: Structures susceptible to fatigue*

EN 12680-3:2011, *Ultrasonic examination – Part 3: Spheroidal graphite cast iron castings*

EN 50308:2004, *Wind turbines – Protective measures – Requirements for design, operation and maintenance*

DIN 50100:2016, *Load controlled fatigue testing – Execution and evaluation of cyclic tests at constant load amplitudes on metallic specimens and components*

FKM Guideline, *Fracture Mechanics Proof of Strength for Engineering Components, 2018 (FKM – RBM-04-18)*

IIW-Doc. 2259-152259-15, *Hobbacher A., Recommendations for fatigue design of welded joints and components, International Institute of Welding, 2014*

IIW-Doc. XIII-2240r2-08/XV-1289r2-08, *Fricke W., Guideline for the Fatigue Assessment by Notch Stress Analysis for Welded Structures, 2010*

VDI 2230-1:2015, *Systematic calculation of highly stressed bolted joints – Joints with one cylindrical bolt*

VDI 2230-2:2014, *Systematic calculation of high duty bolted joints – Joints with several cylindrical bolts*

VDMA 23902:2014, *Guideline for fracture mechanical strength assessment of planet carriers made of nodular cast iron EN-GJS-700-2 for wind turbine gear boxes, Verband Deutscher Maschinen- und Anlagenbau e.V.*

3 Terms, definitions, symbols and abbreviated terms

For the purposes of this document, the following terms and definitions apply.

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

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

3.1 Terms and definitions

3.1.1

basquin equation

power law representation of S-N curves

3.1.2**component capacity**

maximum static stress the component can withstand

3.1.3**damage equivalent load**

equivalent constant range load

load which when repeated a certain number of cycles, causes the same amount of damage as the original combination of several loads and cycles

3.1.4**defect model**

model which is used to substitute the geometrical dimensions of an idealized defect type

3.1.5**design life**

minimum intended life of the structure, as used in the design process that the structure shall survive under fatigue

3.1.6**design load**

mechanical loads whether dynamic or static that the structure shall withstand in its design life

3.1.7**failure assessment diagram****FAD**

diagram which is used to check if there is any risk of brittle failure or plastic collapse while performing a fracture mechanic strength assessment

3.1.8**fail-safe**

design property of a structure or system which prevents its failure

3.1.9**global stresses**

stresses in terms of nominal stresses which are applicable for simple continuous structures (e.g. beams, shells, plates), where the stress can be derived out of sectional forces by analytical methods

Note 1 to entry: Notch factors may need to be considered.

3.1.10**impact energy**

energy absorbed/required to break a V-notched test sample on pendulum impact testing machine

3.1.11**limit state**

state of a structure beyond which it no longer satisfies the design requirements

3.1.12**local stresses**

local stress analysis points at specific regions of a global structure (e.g. at radii, notches) with consideration of the notch shape

3.1.13**mode I**

failure mode I

crack opening mode (in tensile direction) in accordance with FKM Guideline of fracture mechanics or BS 7910

3.1.14**Paris-Erdogan equation**

equation used to compute the cyclic crack growth behaviour

3.1.15**primary structures**

structures which are in the main force flow of the nacelle structure (e.g. the planet carrier of the gearbox)

3.1.16**S-N curve**

relation between the number of stress cycles a material can undergo before failure

3.1.17**safe-life**

design life period of a system after which it should be removed from service

3.1.18**secondary structures**

structures which are not in the main force flow of the nacelle structure (e.g. the housing of the gearbox)

3.1.19**structural model**

model oriented to the shape and dimensions of the defect surrounding structure

3.2 Symbols and abbreviated terms

COV	coefficient of variation
EPFM	elastic plastic fracture mechanics
FAD	failure assessment diagram
FE	finite element
FEA	finite element analysis
LEFM	linear elastic fracture mechanics
LRF_f	load reserve factor against fatigue load
LRF_u	load reserve factor against ultimate load
LRF_{full}	load reserve factor with the full detailed model
$LRF_{simplified}$	load reserve factor with the simplified model
LSE	limit state equation
PSF	partial safety factor
$M_{\delta mf}$	mean value of δmf
RNA	rotor nacelle assembly (herein used without inclusion of blades)
S/N	stress cycle curve for fatigue of materials

a	depth of surface cracks, half depth of embedded cracks/ continuous embedded cracks	mm
a_0	initial crack length	mm
a_{crit}	critical crack length/limiting crack depth	mm
a_{end}	calculated crack length after calculated lifetime	mm
A	elongation at fracture	%
c	half crack length of surface and embedded cracks	mm
C	constant value in crack growth law, e.g. Paris-Erdogan equation	
da/dN	crack growth rate per load cycle	mm/load cycle
D	accumulated damage	-
E	modulus of elasticity (Young's modulus)	MPa
h	location of the crack in the depth direction	mm
L_r	FAD parameter, ratio of applied load to plastic limit load	-
J	J-Integral	kJ/m ² , N/mm
K	stress intensity factor	Mpa·m ^{0,5}
K_C	fracture toughness	Mpa·m ^{0,5}
K_I	stress intensity factor for crack opening mode I (tensile mode)	Mpa·m ^{0,5}
K_{IC}	fracture toughness for crack opening mode I (tensile mode)	Mpa·m ^{0,5}
K_r	FAD parameter, ratio of applied SIF to fracture toughness K_{mat}	Mpa·m ^{0,5}
K_{mat}	characteristic value of fracture toughness	Mpa·m ^{0,5}
K_v	impact energy	Joule, Nm
m	slope of S/N curve	-
M	mean stress sensitivity	-
n	exponent in crack growth law according to Paris-Erdogan equation	-
n_i	counted number of fatigue cycles in load bin i	-
N_D	number of cycles at knee in characteristic stress-life curve for test specimens, from constant amplitude tests	-
N_i	endurable number of cycles at the i^{th} load level, derived from the S/N curve	-
R	stress ratio	-
$R_{p0,2}$	yield strength	MPa
$V_{\delta_{\text{mf}}}$	coefficient of variation of δ_{mf}	
t	thickness of defect model	mm
Z	reduction of area at fracture	mm ²
γ_f	partial safety factor for loads	-
γ_n	consequence of failure factor	-
γ_M	partial safety factor accounting for uncertainties in the material parameters and resistance models	-
$\gamma_{\text{modelling}}$	partial safety factor accounting for simplifications in the load effect model	-

γ_{mt}	product of partial safety factors of $\gamma_{modelling}$ and γ_M	
δ_{mf}	ratio of load reserve factor with full model to load reserve factor with simple model	
ΔK	cyclic stress intensity factor	MPa·m ^{0,5}
β^t	annual reliability index	
ΔK_{th}	threshold value under cyclic loading	MPa·m ^{0,5}
ε_{lim}	total strain limit	%
ρ	plasticity interaction factor	-
σ_a	amplitude of occurring stress cycle	MPa
σ_A	design fatigue strength of component at N_D cycles	MPa
$\sigma_{A,R}$	value of σ_A relevant to loading cycles with minimum/maximum ratio R	MPa
σ_I	relevant stress for crack opening mode I (tensile mode)	MPa
σ_D	endurance limit at knee point of the constant amplitude S/N curve	MPa
σ_{lim}	component capacity (e.g. yield strength, tensile strength) in terms of limiting stress level	MPa
σ_m	mean stress	MPa
σ_L	component stress (e.g. von Mises equivalent stress, first principal stress)	MPa
σ_{ref}	net section stress	MPa
σ_Y	yield strength of the material	MPa

4 Reliability considerations

4.1 Approaches to reliability based design

Structures comprising the nacelle and hub components shall fulfil a set of requirements related to functionality, sustainability and integrity under normal and abnormal events. In addition, the RNA structure should fulfil a certain level of reliability balancing cost (amount of structure) and the risk of failure (likelihood of a critical failure). This is conducted through structural reliability assessments of models established for different limit state functions.

The RNA structure shall be evaluated for the limit states given in IEC 61400-1:2019 (7.6.1.1) and the structural analysis and reliability assessment shall be based on ISO 2394 and IEC 61400-1:2019, 7.1. For completeness, the limit states as described in IEC 61400-1:2019 are given below:

- analysis for ultimate strength,
- analysis for fatigue failure,
- stability analysis (e.g. buckling),
- critical deflection analysis.

Further elaboration of these limit states can be found in ISO 2394.

Three approaches for structural design assessment may be implemented as stated in ISO 2394:

- the risk informed approach,

- the reliability-based approach (probabilistic design),
- the semi-probabilistic approach (deterministic design).

Although all three approaches may be applied, wind turbine design including RNA design either follows the reliability-based -or semi-probabilistic approach. For semi-probabilistic approach, structural design standards shall be used i.e. IEC 61400-1:2019 or Eurocodes.

Reliability based assessment shall use uncertainty models which shall describe the structure and its behaviour, through which the design requirements of the structure are quantified, considering external relevant conditions. Those uncertainty models can be represented by stochastic variables or processes and a limit state approach to model the relevant failure scenarios.

Models may be simplified considering decisive factors and neglecting those factors with low impact, based on proper studies. Uncertainties quantification should follow the guidance given in ISO 2394 and IEC 61400-1:2019, Annex K.

The requirements for each LSE shall be consistent with the design equations following deterministic codes of practice as IEC 61400-1 or equations resulting from specific studies where response function of such components to different inputs are derived e.g. Petersen-Seidel (IEC 61400-6:2020) for bolt connections.

Limit state equations are built based on models describing the limit state for structural verification. A LSE with relevant basic parameters (X) is expressed as:

$$g(X) \leq 0 \quad (1)$$

where $g(X) < 0$ represents failure, in other words, an adverse state. Different forms of LSE can be found:

- those separated into one resistance function, $r(\alpha)$, and one load effect function, $s(\sigma)$, e.g. yielding limit, leading to the following expression form:

$$r(\alpha) - s(\sigma) \leq 0 \quad (2)$$

- those where a certain resistance-load effect function should comply to a given limit (ε), e.g. fatigue and Petersen-Seidel, leading to the following expression:

$$\varepsilon \pm f[r(\alpha), s(\sigma)] \leq 0 \quad (3)$$

These types of LSEs are specific to structural/component failure modes, where uncertainties related to resistance, load effect and models shall be defined.

Different LSEs for yielding and fatigue failure criteria are shown in Annex D.

RNA component reliability analysis shall follow the framework specified in ISO 2394:2015, 8.5. The following steps for component reliability analysis are recommended:

- 1) Select appropriate limit state function;
- 2) Specify appropriate time reference;
- 3) Identify basic variables and develop appropriate probabilistic models;
- 4) Compute reliability index and failure probability;
- 5) Perform sensitivity studies.

4.2 Models and basic variables for structural verification

4.2.1 Reliability assessment

Reliability assessment of RNA components shall consider calculation models describing its physical behaviour, which can be categorized as:

- actions and environmental influences,
- geometrical parameters,
- material and resistance properties, and
- active and passive control measures.

A description of each one of those physical behaviours and their models should follow those in ISO 2394.

4.2.2 Material properties

Material parameters shall be modelled by stochastic variables if a reliability-based approach is used and by characteristic/nominal values and partial safety factors if a semi-probabilistic approach is used for design. When a limit state verification is sensitive to the variability of a material property, the variability of the material property should be taken into account in a reliability assessment. Unless otherwise stated, where a low value of material or product property is unfavourable, the characteristic value should be defined as in IEC 61400-1:2019, Clause K.11.

If non-standardized material properties need to be used, then the material property values shall be determined from standardised tests performed under specified conditions, specifications of which are described in Clause 8.

4.3 Partial safety factors and reliability targets

In a semi-probabilistic approach, partial safety factors should follow those specified in recognized standards, which possess at least the reliability levels required in IEC 61400-1 or may be calibrated to a specific reliability level through a reliability-based approach i.e. as in IEC 61400-1:2019, Annex K or ISO 2394.

Target levels for reliability index β shall be based on annual failure probabilities. Different target reliability levels should be considered based on its component class classified as in Table 1. The maximum recommended annual probability of failure target for component class 2 is 5×10^{-4} ($\beta = 3,3$) as given in IEC 61400-1:2019. The annual target reliabilities for component class 3 and component class 1 may be obtained from ISO 2394.

Table 1 – Component classes as in IEC 61400-1:2019

Component class	Description
1	"fail-safe" structural components whose failure does not result in the failure of a major part of a wind turbine
2	"safe-life" structural components whose failure may lead to the failure of a major part of a wind turbine
3	"safe-life" mechanical components that link actuators and brakes to main structural components for the purpose of implementing non-redundant wind turbine protection functions

5 Application of loads and analysis models

5.1 Loads models

The loads applied on RNA components shall be determined through aeroelastic models checking for at least the critical design load cases specified in IEC 61400-1:2019. Additional load requirements for offshore applications shall be included according to IEC 61400-3-1 or IEC TS 61400-3-2. The methods used for load application shall ensure that the mechanical behaviour of the component accounts for potential non-linearities in the structure and ensure that the load path is simulated correctly.

Simplifications to the analysis model may be performed along with proper load application safety factor as described in 5.4.

5.2 Analysis model

5.2.1 General

The analysis model shall account for all relevant load bearing and stiffening components, and for the relevant supporting and constraining effects. The degree of subdivision shall take into account the geometry of the structure and its influence on the load distribution and application, the distribution of external loads, and expected stress pattern. Elements or members considered as being of secondary importance shall be accounted to assess whether they have an influence on stress distribution or inertial effect on the structure.

5.2.2 Load path modelling

Models used in the analysis of a given component shall include:

- relevant loads with the appropriate distribution over the component,
- supporting effects from other components with accurate stiffness to ensure that the component deforms correctly and is not affected by boundary conditions,
- relevant non-linear stiffness effects from other components and contacts (e.g. bolted connections and bearings),
- local deflections from other components (e.g. out of plane deformations in thin walled structures and local bending of blade roots at the bearing interface).

5.2.3 Application of load components

A load component may be represented by a force, moment, deformation or equivalent at a specific location with a specific direction.

Relevant load components and appropriate approaches for load effect calculations shall be considered for structural component verification, (e.g. loads at main bearing for the verification of the nacelle front structure). This cross-section load shall be connected to a supporting component to avoid deviation effects from boundary conditions.

Load components which contribute to the damage of the component shall be included. Load components may be omitted by introducing an additional safety factor as described in 5.4.

5.2.4 Boundary conditions

Constraints on the FE model shall be applied in sufficient distance from the analysed component in order not to influence its behaviour. Internal boundary conditions may be used to stabilize the FE model but shall not prohibit the correct load path.

5.3 Modelling of nonlinear mechanical behaviour

5.3.1 General

Nonlinearities in the load effect shall be taken into account. Simplifications may be implemented with further considerations on *PSF* based on results deviations compared to results where nonlinearities are considered. Linear superposition principle does not generally apply for non-linear behaviour.

5.3.2 Nonlinear stress effects

The structural assessment requires identification of non-linear effects of structural members that affect the components to be verified, and load components that cause inaccuracies in linear superposition of stresses.

These non-linear effects are often found in relation to:

- bearings, where radial loads cannot be superpositioned,
- contacts, where opening or sliding causes non-linear stiffness,
- material behaviour, as plastification, which affects material stiffness,
- buckling or large deflections causing non-linear stiffness,
- mechanisms with non-linear stiffness.

To simulate these effects accurately, the applied loads should be defined with the expected values without scaling and with contemporary loads to avoid superpositioning errors.

Different levels of the load components or combinations should be considered in ultimate and fatigue analyses thereof where the structure exhibits non-linear behaviour to describe the load-stress relation accurately and to locate potential weak spots in the structure.

5.3.3 Application of ultimate loads

The ultimate limit state of nacelle and hub components, also referred as extreme analysis, shall be simulated with contemporaneous load components for each load case. Guidance for the derivation of extreme design loads from contemporaneous loads can be found in IEC 61400-1:2019, Annex I. Superposition and linear extrapolation of load components shall only be used for structures with a linear behaviour at the expected load levels for extreme analysis.

All relevant loading scenarios according to IEC 61400-1:2019 shall be considered for each component.

5.3.4 Application of fatigue loads

The method for fatigue assessment should be based on the given load component for verification, its potential non-linear effects and load components combination to avoid inaccuracies from linear superposition.

Non-linear effects may be computed from load-stress relations created from multiple load levels. The number and magnitude of the load levels shall be defined for the relevant component according to the expected fatigue loads on the component, so that stress-time functions may be created by interpolation between multiple load components and levels.

Fatigue assessment shall be performed, with all relevant load components, using at least one of the following methods:

- stress-time series, created directly through models analysed for the whole-time domain loads,
- stress-time series, created from load-stress relations with the simulated load-time values. This allows for assessing non-linear effects and load component interaction,
- stress spectra, created from superposition of individual load component spectra determined by rainflow counting. This allows for simulating non-linear effects for individual load components but not load component interaction,
- damage equivalent load (constant range load) with a slope defined from the relevant SN curve for the component material. This method requires that the structure exhibits linear behaviour under fatigue loading.

Damage accumulation should be performed using Palmgren-Miner damage criterion or Fracture mechanics approach for crack growth depending on the application.

5.4 Partial safety factors

Simplified models/methods may be implemented; however, load effect evaluation from simplified models shall be checked against a verification model [1]¹, which strictly follows modelling conditions mentioned in IEC 61400-1:2019. i.e., accounts for non-linear effects, mesh convergence with the numerical models, amongst others.

In case of using a simplified model, the material partial safety factor shall be modified to be a function of factors $\gamma_{mt} = \gamma_M \times \gamma_{modelling}$, where γ_M represents the material partial safety factors from IEC 61400-1:2019, $\gamma_{modelling}$ is a partial safety factor which accounts for the load effect deviations due to simplification. Where a simplified model does not reduce the annual reliability below that of IEC 61400-1:2019, $\gamma_{modelling} = 1$ may be used. A list describing the potential source of load effect deviations is presented in Table 2.

If a detailed model verification is applied, and numerous test cases results are available from the detailed model (LRF_{full}) and numerical calculations are performed for each test case ($LRF_{simplified}$), the $\gamma_{modelling}$ factor may be calculated based on statistical evaluation of the verification/simplified domain.

In first place, the ratio of the results from the verification model and the numerical simulation should be calculated for each sample (n) following Formula (4). Secondly, stochastic parameters are identified for the set of sample points (δ_{mf}) i.e. COV ($V_{\delta_{mf}}$) and mean value ($M_{\delta_{mf}}$) which should be derived assuming a lognormal distribution. The number of evaluation points shall be greater than 10 and they shall be near the characteristic conditions.

$$\delta_{mf} = \frac{LRF_{full}}{LRF_{simplified}} \quad (4)$$

¹ Numbers in square brackets refer to the Bibliography.

where

LRF_{full} is the load reserve factor with the full detailed model;

$LRF_{simplified}$ is the load reserve factor with the simplified model.

The values of the modelling partial safety factors are presented in Table 3 and Table 4 for yielding and fatigue failure mode, respectively, for different uncertainties of δ_{mf} , i.e. COV – ($V_{\delta mf}$) represented in Formula (4) and mean value – ($M_{\delta mf}$) represented in Formula (4) calculated for an annual target reliability index of 3.1.3.

An example of the implementation is shown in Annex E.

Table 2 – List of potential sources for modelling deviations

Description	Cases
External loads	Excluding load components due to unavailability from the aeroelastic modelling (not quantified) or low impact on stress
	Simplified load component effect, e.g. quantified linearization of the load effect into the stress
Effect of external loads to analysis result	Direction simulation results, no scaling of load components
	Scaling approach with multiple or single load points
	Combination of load components: simultaneous load sensors, superposition of individual loads simulations, etc.
Numerical modelling accuracy	Supporting component effects
	Stress convergences and structure model type
Failure analysis method accuracy	Stress time series
	Stress spectra
	Damage equivalent load
	Contemporaneous load components

**Table 3 – Modelling partial safety factor $\gamma_{modelling}$: yielding
where coefficient of variation of yield strength is less than 15 %**

$M_{\delta mf} / V_{\delta mf}$	$\leq 5 \%$	$5 \% < V_{\delta mf} \leq 10 \%$	$10 \% < V_{\delta mf} \leq 15 \%$	$15 \% < V_{\delta mf} \leq 20 \%$
$1 < M_{\delta mf} \leq 1,02$	1,00	1,05	1,1	1,18
$1,02 < M_{\delta mf} \leq 1,05$	1,05	1,08	1,13	1,2
$1,05 < M_{\delta mf} \leq 1,10$	1,12	1,16	1,21	1,3
$1,10 < M_{\delta mf} \leq 1,15$	1,26	1,3	1,36	1,46

Table 4 – Modelling partial safety factor, $\gamma_{\text{modelling}}$: fatigue of welded details and cast iron

$M_{\delta mf} / V_{\delta mf}$	$\leq 5\%$	$5\% < V_{\delta mf} \leq 10\%$	$10\% < V_{\delta mf} \leq 15\%$	$15\% < V_{\delta mf} \leq 20\%$
$1 < M_{\delta mf} \leq 1,02$	1,00	1,03	1,08	1,15
$1,02 < M_{\delta mf} \leq 1,05$	1,04	1,06	1,11	1,18
$1,05 < M_{\delta mf} \leq 1,10$	1,08	1,11	1,16	1,22
$1,10 < M_{\delta mf} \leq 1,15$	1,13	1,16	1,22	1,29

5.5 Partial safety factor for resistance

Partial safety factors for resistances shall be selected following IEC 61400-1:2019. For cases with ductile failure modes and yield strength lower than 90 % of the ultimate strength, the partial safety factor for resistance, γ_M , shall be not less than 1,1 with survival probabilities of 95 % and above. The required survival probabilities and confidence levels stated in this document are minimum values and shall be adapted in case the related applied design standard requires more conservative values. For buckling, the partial safety factor for resistance shall be chosen as per IEC 61400-1, unless it can be shown to be lower with appropriate data.

For fatigue verification, partial safety factor for resistance, γ_M , shall be not less than those presented in Table 5 based on given survival probabilities of the characteristic S-N curve and the standard deviation of the logarithm of the S-N curve material constant K. Values in Table 5 are obtained based on the resultant COV for fatigue stress ranges between 15 % to 20 %. For different values of IEC 61400-1:2019, Table K.3 should be followed. Table 5 and Table 6 are calibrated with the 90 % quantile of wind turbulence. It is possible to re-derive the values given in these tables also using a full distribution of wind turbulence.

Table 5 – Minimum resistance partial safety factors, γ_M , for welded steel for different survival probabilities of the characteristic S-N curve

Standard deviation log K	50 %	95 %	97,7 %
0,2	1,70	1,35	1,25

Table 6 – Minimum resistance partial safety factors γ_M , for cast iron, forged and steel components (if not utilizing relevant design standards such as EN 1993-1-9) for different survival probabilities of the characteristic S-N curve

Mean stress effects on damage insignificant (R is near -1)			
Standard deviation log K	50 %	95 %	97,7 %
0,2 to 0,3	1,70	1,35	1,30 ²
Mean stress effects on damage is significant			
Standard deviation log K	50 %	95 %	97,7 %
0,2 to 0,3	1,70	1,40	1,35

2 $PSF = 1,25$ is acceptable if it can be shown that the design loads are not governed by wind turbulence. For example, showing the change in design loads obtained while using 90 % wind turbulence input versus 50 % wind turbulence input is less than a tolerant value.

5.6 Nacelle and hub component considerations

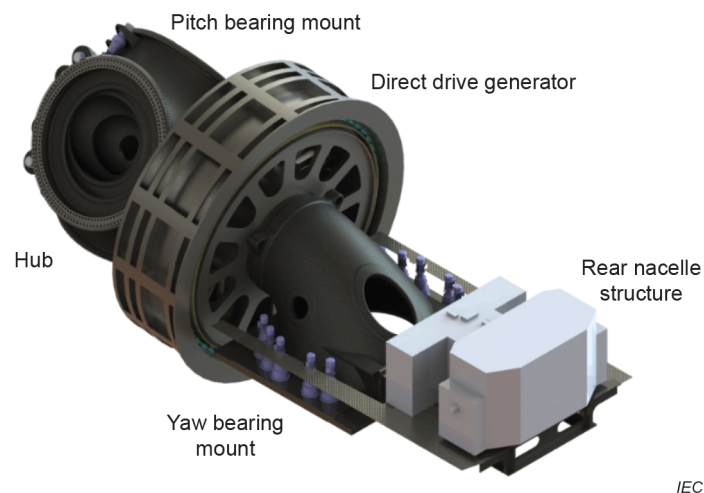
5.6.1 General

A set of considerations shall be taken into account in models representing the different RNA components. The most critical elements are mentioned in the subsequent subclauses. A typical nacelle layout is depicted in Figure 1 for clarity.

5.6.2 Hub structure and bolts

Hub structure comprises the components, including bolts in the load path between blade root and main shaft.

- The effects of blade bearings require that bending moments are combined, and multiple load levels shall be simulated.
- The proximity of the blades requires that the load interaction between blades shall be assessed.
- Difference in edge and flap stiffness of blades requires additional FE models to evaluate load scenarios with pitched blades.
- Constraining effects in the nacelle structure shall simulate the support from bearings.
- Pitch mechanism loading scenario shall include potential faults.
- Blade locking mechanism load cases shall include service and fault scenarios and simulate the correct load path.
- Transportation and installation loading scenarios for blades and hub shall include the relevant load introductions and supports.



NOTE The load carrying parts of the nacelle structure are denoted. The support for the auxiliary equipment such as hydraulic systems, power converter and transformer is denoted the nacelle rear structure. Reproduced from the INNWIND.EU project [www.innwind.eu]

SOURCE: Figure provided by the FP7 INNWIND.EU project coordinators at DTU Wind.

Figure 1 – Illustration of a nacelle structure, where for example a direct drive generator is mounted behind the hub

Safety attachment points of the nacelle shall be verified by analysis with loading in accordance with EN 50308:2004 or alternatively be load tested and approved.

5.6.3 Nacelle front structure (alternatively: mechanical drive-train structure)

The nacelle front structure comprises the components, including bolts, which transfer the loads between the hub to the yaw mechanism and the tower.

- Effects from load application by individual blade loads compared to main bearing loads shall be considered for certain components.
- Bearings require that bending moments are combined, and multiple load levels included.
- Constraining effects in yaw system and tower shall support the nacelle front structure (or mechanical drive train structure) with the correct stiffness for simulated load levels.
- Load cases for rotor lock mechanism shall include service and fault scenarios and simulate the correct load path.
- Rear structure supporting stiffness and mass distribution shall be considered.
- Loading on the rear structure shall be included, e.g., by applying linear accelerations and angular accelerations.
- Transportation and installation loading scenarios for nacelle front structure (or mechanical drive train structure) shall include the relevant load introductions and supports.

5.6.4 Gearbox structure

The gearbox structure transfers the loads from the rotating structure into the fixed structure. At least the following model considerations shall be considered if they contribute to the damage of the component:

- relevant effects of deflections or misalignment,
- generator effect on the high speed shaft, usually by means of a coupling,
- interaction with nacelle front structure via torque arm and low speed shaft,
- load cases with activated mechanical brake to simulate the correct load path,
- installation DLCs according to the rotor installation process.

5.6.5 Yaw structure

The yaw structure comprises the components, which transfers the loads from the nacelle front structure and into the tower, excluding the yaw bearing (see IEC 61400-1).

- The correct load path of yaw moments in the yaw mechanism and bending moments in the yaw bearing respectively shall be modelled by simulating the stiffness and mechanical behaviour of the components in the yaw system.
- Distribution of yaw loads between yaw mechanism components shall be considered.
- Resulting loads obtained from combining the different applied load components e.g., main bearing loads and accelerations, shall match the resulting loads observed in the yaw cross section.
- For the yaw system, the bending moments shall be combined, and multiple load levels included.
- Constraining effects in the tower shall support the yaw structure with the correct stiffness for simulated load levels.
- Accurate mass and centre of gravity of rotor and nacelle shall be ensured in the simulation.

5.6.6 Nacelle rear structure

The nacelle rear structure comprises the structural components in the nacelle which does not transfer the loads between the hub and the tower, but transfers loads from nacelle components e.g., transformer, generator, converter, cooling system, among others, into the nacelle front structure (or mechanical drive train structure). This excludes cover components.

- Accurate mass and centre of gravity of all relevant components in the rear structure shall be ensured.
- Dynamic effect shall be considered if relevant to the rear structure.
- Front structure interfaces stiffness shall be considered.
- Nacelle cover supporting effect shall be investigated and it shall be included if the impact is significant.
- Transportation and installation loading scenarios for nacelle rear structure shall include the relevant load introductions and supports.

5.6.7 Nacelle cover and spinner

The nacelle cover and spinner comprise the components functioning as protection of the nacelle from the external environment. It also comprises the transition components used for its mounting on the RNA.

- Analysis model for nacelle cover and spinner shall include sufficient part of support structure to simulate the load path accurately.
- Ultimate wind conditions shall be simulated in accordance with IEC 61400-1 and IEC 61400-3-1 applied as surface pressure with relevant aerodynamic coefficients for every part of the surface. The applied surface pressure may alternatively also be derived from adequate CFD analysis. Surface pressure or aerodynamic coefficients can also be derived from wind tunnel test or relevant building codes with an adequate representation of the cover shape.
- Floors and regular working platforms in the nacelle cover and spinner should comply with the live loading requirements from EN 50308:
 - concentrated characteristic loads of 1,5 kN over 0,2 m × 0,2 m;
 - evenly distributed characteristic loads of 3 kN/m² over an area representing the working area.
- Safety attachment points shall be verified by analysis with loading in accordance with EN 50308, CEN/TS 16415 or equivalent standards or alternatively be load tested as per relevant national standards.
- Load scenario simulation of potential accumulated spillage fluids shall be considered.
- Ultimate environmental loads shall be applied with a realistic magnitude. Surfaces where snow or ice can accumulate shall be verified with an evenly distributed surface design load of 3 kN/m² despite the elevation from ground. Different load settings taken from local standards or sufficient measurements on snow accumulation may be implemented.

Snow loads may be neglected for nacelle and spinner cover surfaces with an inclination above 45°.

6 Deflection analysis

Parts of the nacelle structure are sensitive to misalignment, and excessive deflection may cause improper function and/or interference with other components. Hence the consideration of deflection and stiffness is important in the design process, e.g. regarding the load density, the load distribution and the reaction of connecting structural members.

It shall be verified that no critical deflections affecting the structural integrity of the nacelle structures occur during the life of the wind turbine. Further guidance on the deflection analysis is provided in IEC 61400-1:2019, 7.6.5.

Deflection points within the nacelle structure that are critical for the gearbox or generator shall be considered to verify that the deflection at these points meets the design constraints for the gearbox, generator and non-structural components of the nacelle. For example, deflections of main shaft, air gap of direct drive generators and deflection of mainframe.

Access areas for personnel should be assessed so as to not exceed deflection limits required in relevant safety standards. The load requirements for deflection analysis are specified in Clause 5. The structural verification requirements that include deflection analysis are elaborated in Clause 7.

7 Strength verification

7.1 General

Strength verification is the comparison of the local design stress of the primary structures and secondary structures against the allowed local limits. Strength verification shall be performed for both ultimate and fatigue loads unless the fatigue calculation can be omitted if the component is primarily loaded by static load cases (e.g. rotor lock, transportation, single blade installation). Other components (e.g. nacelle cover) may be verified by appropriate load cases and strength requirements.

The mechanical load on the component shall be applied as discussed in Clause 5.

The partial safety factors γ_n (consequence of failure) and γ_M (materials) shall be in accordance with this document and IEC 61400-1:2019.

The presented design methods do not cover the effect of corrosion; therefore, all components shall be protected adequately against corrosion according to the appropriate standards, for example, ISO 12944-5 [2], ISO 1461 [3], ISO 14713-1 [4].

7.2 Determination of stress and strain

Component stress is affected by design and internal loads and by relative displacements of the interfaces. They can either be regarded as local stresses or global stresses. The stress level depends on loads, shape, material properties and boundary conditions.

The stress and strain shall be calculated by using appropriate mathematical models or numerical analysis tools, such as FEA.

7.3 Material properties

7.3.1 Material data

Material data shall be taken from internationally recognized standards or data from material tests according to Clause 8, considering the required survival probability and related safety factors.

The manufacturing process of cast iron with spheroidal graphite shall ensure that at least 90 % of the graphite has been segregated in the spheroidal form V and VI and in the spheroidal size between 5 and 7 according to ISO 945-1:2019. For larger wall thicknesses, requirements may be specified as per 8.1. For the ferritic types, the pearlite proportion within the grain structure of the metallic base material shall not exceed 10 % following ISO 1083:2018.

7.3.2 Influence of size

Mechanical properties are size dependent. When the size effect is not experimentally quantified, the influence of the size on the material strength is taken from internationally recognized standards, or determined by testing methods, see Clause 8.

7.4 Static strength assessment

7.4.1 Assessment process

The determination of the reserve factor is a necessary step to avoid a major failure in the wind turbine. The static strength assessment shall be in accordance with this document or other internationally recognized standards. Static strength assessment should be performed for those load combinations which result in the highest local stress for linear elastic behaviour or local strain if plastification needs to be considered. Nominal stresses may be used where applicable. Further information about the limit state function is given in Clause 4. For global and local failures, Annex F may be taken as guidance.

7.4.2 Cast, forged and steel components

7.4.2.1 Design criteria

The design criteria of the structural component shall be calculated in accordance with IEC 61400-1:2019, Formula (32) with respect to the component capacity, component stress and the relevant partial safety factors.

The reserve factor LRF_u for ultimate strength (or yield strength, where applicable) can be defined³. This only applies to linear elastic calculations.

7.4.2.2 Partial safety factors for spheroidal graphite cast iron, forged and steel components

For steel, forged components and spheroidal graphite (nodular) cast iron, the yield strength shall be used as static strength criteria considering the relevant safety factors.

All partial safety factors shall be in accordance with this document and IEC 61400-1:2019.

7.4.2.3 Partial safety factors for grey cast iron

The usage of grey (lamellar) cast iron is restricted to secondary structures, such as the gearbox housing. σ_{lim} is defined by the tensile/compressive strength of the material.

The partial safety factor γ_n shall be based on IEC 61400-1:2019. The partial safety factor γ_M shall be taken as 1,3.

³ The reserve factor can be formulated in general as:

$$LRF_u = \frac{\sigma_{lim}}{\sigma_L \times \gamma_{res}} \geq 1$$

where

- σ_{lim} is the component capacity or static strength criterion (e.g. yield strength, tensile strength);
- σ_L is the component stress (e.g. Mises-stress, first principal stress);
- γ_{res} is the product of the relevant partial safety factors.

7.4.2.4 Stress hypothesis for ultimate or yield strength

The dimensioning of a structure or component depends on the type of possible failure. The static strength assessment should be carried out using a stress hypothesis appropriate to the type of failure, considering the material behaviour as ductile or brittle. The criteria and measures for the definition of the material shall correlate to 7.6.

- For brittle materials, the behaviour of the material is described by the maximum principal stress hypothesis. Both maximum and minimum principal stress should be considered in the strength verification.
- For ductile materials, the maximum shear strain energy hypothesis (e.g. von Mises) or the maximum shear stress hypothesis (e.g. Tresca) describes the failure mechanism.

Alternative hypothesis may be applied if they are proven by testing specimens that are representative of the assessed component.

7.4.2.5 Plastic deformation

If the yield stress is exceeded locally, the notch stress and strain will have a non-linear relation to the load level due to local yielding. The local strain shall be considered for assessment of the static strength on the component. It shall be taken into account that the local strain distribution depends on the material, the component shape (i.e. notch) and on the load level.

The total strain limit is $\varepsilon_{lim} = 1\%$ for ductile materials. In all cases, this is limited to minor plastifications, resulting from extreme load cases at local notches. However, for hotspots primarily loaded by extreme events (e.g. rotor lock), a higher total strain limit may be defined. For materials with an elongation at fracture $> 8\%$, the total strain limit of 1% may be applied as a design criterion only if it is confirmed that the stress (from the stress-strain curve) at 1% total strain is less than the ultimate stress divided by a partial safety factor of 1,3 or otherwise proven by experimental tests that reflect the actual component stress state.

The total strain limit may be elevated if this is proven by testing specimens that are representative of the assessed component.

For the evaluation of the plastic deformation, a nonlinear calculation using a characteristic elastic-plastic stress-strain curve shall be performed. Unless a stress-strain-curve based on tests is considered, see Clause 8, an idealized elastic plastic stress-strain curve similar to that of Figure 2 may be used. Other stress-strain relations (e.g. Ramberg Osgood) may be used if applicable. For notches, the Neuber concept using section factors for local failure may be applied.

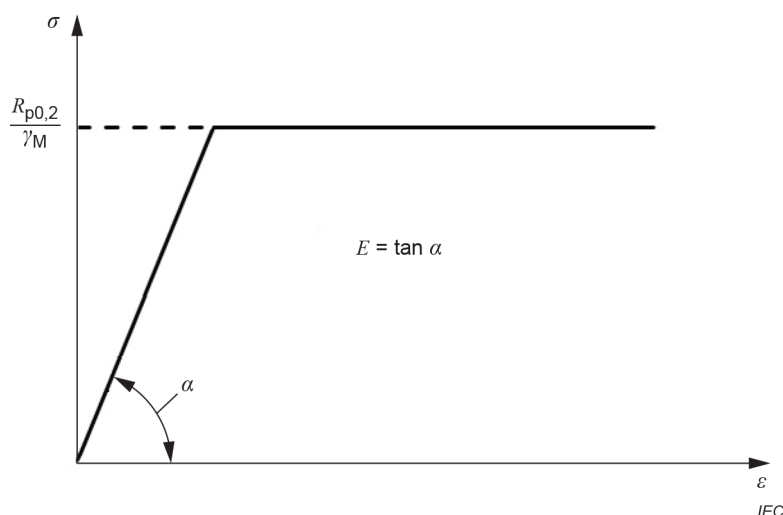


Figure 2 – Idealized elastic plastic stress-strain curve



Partial safety factors shall be applied on the load side for nonlinear calculations. In case of a bilinear material curve, it may also be applied on the $R_{p0,2}$ value. This shall be done in accordance with Clause 5.

The following influences shall be considered:

- Residual stresses/stress relocation shall be considered in a conservative manner. For consideration of beneficial effects, stability of the residual stresses shall be proven.
- Influence on fatigue life shall be evaluated.
- The stress time series of the fatigue and extreme load events shall be analysed to detect any stress conditions which exceed the static yield limit or lead to a reversal of the plastification, which shall be avoided, unless verified.
- Load cycles exceeding yield limit in the fatigue regime shall be avoided for the stress-based approach considering linear damage accumulation unless validated.
- The permissible strain depends on the function of the structure, so that, in the case of permanent elongation, proof of operability shall be given for the component and its adjacent components.

7.4.3 Welded structures

The stress calculation in welded structures shall be in accordance with standards such as Eurocode 3, IIW-Doc. 2259-15/2259-15 and IIW-Doc. XIII-2240r2-08/XV-1289r2-08.

7.4.4 Bolted joints

The analysis shall be based on standards or guidelines such as VDI 2230-1 and VDI 2230-2, EN 1993-1-8. Care should be taken when developing simulation models based on the relevant guidelines outlined, as each standard employs different concepts and assumptions in the stress analysis. Beside the stiffness of the mating components, the bolt stiffness shall be represented appropriately (longitudinal and bending stiffness) and the stiffness of the whole bolt assembly (nuts, screw head, thread) should also be taken into account, especially for joints with relatively short clamping lengths. Importantly, the simulated preload forces are dependent on the joint-tightening process, and care should be taken when determining and applying this in the model. The value of the preload force should be conservatively set depending on the failure mode under evaluation, unless a full probabilistic analysis is carried out.

Bolted joints in terms of friction, form locking or combination of both are not covered by this subclause.

Main analysis points include:

- Axial load based calculation on the critical bolt cross section including bending load, if required in the selected normative reference mentioned above.
- Axial load applied to the stress-relevant cross section of the thread (for the case where the thread is the critical cross section). Otherwise, the smallest cross-section shall be used (e.g. extension or necked-down bolts).
- Stripping of threads shall be verified and the minimum length of engaged threads dimensioned accordingly.

In general, two analysis limits are possible: elastic and plastic.

In the case of elastic analysis, the bolt should remain elastic (no loss of preload) and the stress should be compared against the yield point. Potential pre-stressing in the form of shear stress due to torsional tightening methods shall also be considered.

Alternatively, the bolt may be strained plastically (accepted loss of preload), as in the case of elastically preloaded bolts. Here ideally plastic behaviour shall be assumed. Based on the maximum preload, the ultimate load leads to plastic flow. The total strain at the bolt section that is exposed to yielding shall remain below 1 % and the loss of preload on the fatigue behaviour shall be considered. For higher strength grades than 10,9, there shall not be any plastic strain considered unless proven by tests.

Due to the extremely flat bolt force to load relationship and the preload of the bolts to the yield point, the minimum partial safety factor of material $\gamma_M = 1,1$ shall be considered and may be applied to the operational load or on the resistance side. If the partial safety factor derived from the used standards or guidelines is higher than the one from IEC 61400-1, then the higher partial safety factor shall prevail.

Evaluation of additional joint components (e.g. expansion sleeve analysis) may also be necessary.

7.4.5 Fibre reinforced material

The static strength of parts from fibre reinforced material shall be verified according to IEC 61400-5 or an equivalent standard. For spinner and nacelle cover, the verification of inter fibre fracture and buckling may be omitted.

7.5 Fatigue strength assessment

7.5.1 Fatigue strength methods

The fatigue strength analysis of structural components in the nacelle should be performed according to this document. Other internationally recognized analysis codes can be applied, if their usefulness for the applied material and specified load conditions is proven. Guidance for fatigue analyses using damage accumulation can be taken from Dowling (1972) [5], Haibach (2006) [6], Matsuishi and Endo (1969) [7] or Wegerdt, Hanel, Hänel, Wirthgen (2003) [8]. For mean stress correction, Clause F.2 of Annex F may be considered as guidance.

The fatigue strength verification for welded structures should be in accordance with standards such as EN 1993-1-9, IIW-Doc. 2259-15/2259-15 and IIW-Doc. XIII-2240r2-08/XV-1289r2-08, DNV-RP-C203 [9]. Informative guidance is provided in Annex B.

The analysis procedure is based on the local stress approach. In this case, the fatigue strength should be described using the accumulated damage, D , and the fatigue reserve factor, LRF_f by using the Miners rule.

It shall be stated explicitly in the calculation whether amplitude (semi-range) or range is used as the measure of fatigue stress magnitude, and any non-conforming data shall be converted appropriately. It is also necessary to include the half load cycles in the calculation. The use of amplitudes is assumed here.

7.5.2 Determination of local stresses

The local stress level (i.e. the component stress) will be determined as described in 7.2.

7.5.3 Stress hypothesis for fatigue

The selection of the stress hypothesis depends on the loading and material type of the component. In general, normal stress in critical plane approach shall be used for brittle material and cast iron, other methods like maximum principal stress, normal stress, etc. may be applied where relevant. For ductile material, several different stress hypotheses are known.

7.5.4 S/N curves

The S/N curves, such as in Figure 3, characterize the fatigue strength of the metallic material.

In alignment with IEC 61400-1, statistically assured S/N curves for the material should be used as a basis. If such S/N curves are not available, synthetic S/N curves in accordance with Haibach (2006), Godehus and Zenner (1999) [10], Wegerdt, Hanel, Hänel, Wirthgen (2003) or similar authoritative reference should be used for fatigue analyses.

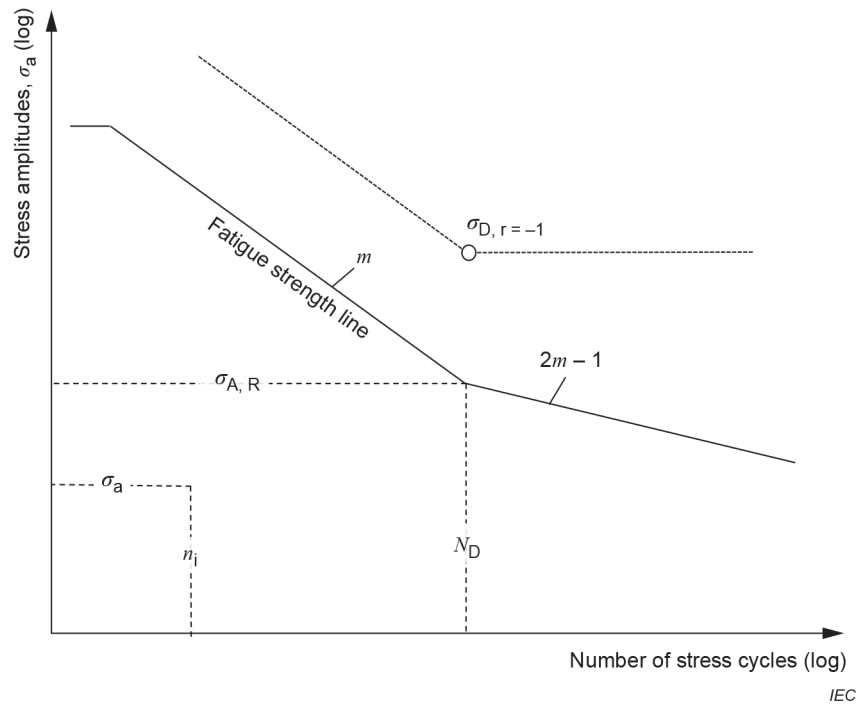


Figure 3 – Representative S /N curve

For stress cycle numbers $n_i > N_D$, the S/N curves can be extended from $\sigma_{A,R}$ with the inclination (slope) parameter $2m-1$, for variable loading, where m is the inclination parameter of the fatigue strength line, Haibach (2006). Here the limiting stress cycle number N_D is the number of cycles at which, under optimum test conditions (no corrosion effect, etc. in accordance with Clause 8), the knee point σ_D of the constant amplitude S/N curve is defined. Further concepts may be used if applicability is proven.

7.5.5 Influence on fatigue strength

The following influences on the fatigue strength and reduction factors represent additional factors for uncertainties and should be considered in the calculation of stress amplitude or stress range unless it can be verified, e.g. by tests, that the influence on the fatigue strength is negligible:

- mechanical stress influence and statistical size influence (stress gradient models and volumetric models),
- surface roughness,
- surface treatment,
- mean stress influence,
- size influence,
- manufacturing quality (e.g. cast quality, weld quality, forging quality).

The interaction of the individual influence factors may be considered by adequate methods if applicability is proven.

7.5.6 Partial safety factors for fatigue

Design S/N-curves for metallic materials may be determined in accordance with 8.3 considering the partial safety factors in Clause 5, Table 6 for the respective survival probability.

For cast iron, along with Table 6, the casting flaws shall be accounted for in the design process. The partial safety factor γ_M in Table 7 should be applied for casting flaws depending on the required local cast quality for S/N-curves. Alternatively, inner flaws may also be assessed by fracture mechanics approaches, see 7.6. Annex D may be used for the calibration of partial safety factor for fatigue.

Intermediate quality classes may be developed, e.g. based on tests or other adequate methods and shall be agreed with the relevant authorities.

The quality level on a component should be verified by non-destructive testing for the determined hot spots. The area to be tested shall be identified in the appropriate manufacturing drawings, either as-cast or as-machined. If a cast quality level of 01 or 2 is used, a 100 % testing shall be applied.

Table 7 – Partial safety factors γ_M for S/N-curves of cast iron materials

Material behaviours	γ_M		
	01	2	3
Cast quality class according to EN 12680-3:2011	01	2	3
γ_M ($P = 50$ %, confidence level ≥ 75 %)	1,7 ^a	2	2,35
γ_M ($P = 95$ %, confidence level ≥ 75 %) if impact of mean stress corrections on damage is insignificant (R is near -1)	1,35 ^a	1,6	1,87
γ_M ($P = 95$ %, confidence level ≥ 75 %) if impact of mean stress corrections on damage is significant	1,4 ^a	1,65	1,94
γ_M ($P \geq 97,7$ %, confidence level ≥ 75 %) if impact of mean stress corrections on damage is insignificant (R is near -1)	1,3 ^a	1,53	1,8
γ_M ($P \geq 97,7$ %, confidence level ≥ 75 %) if impact of mean stress corrections on damage is significant	1,35 ^a	1,6	1,87
γ_M ($P \geq 97,7$ %, confidence level ≥ 75 %) if damage is not governed by mean stress corrections and design loads are shown to not be influenced by wind turbulence. For example, showing the change in design loads obtained while using 90 % wind turbulence input versus 50 % wind turbulence is less than a tolerant value.	1,25	1,47	1,73
UT/MT/PT quality level is limited to level 3 in general. For the UT quality level 3 area, MT/PT quality level will be limited to quality level 3. For the UT quality level 01 and level 2 area, MT/PT quality level will be limited to level 2. This will ensure that in the respective UT quality level area, the more critical surface flaws detected by MT/PT are not allowed to be bigger than internal flaws detected by UT. For machined surfaces, the worst acceptable are quality levels SM/LM/AM 2 according to EN 1369:1996 or SP/CP/LP/AP 2 according to EN 1371-1:1997. The quality levels LM/AM according to EN 1369:2012 and LP/AP according to EN 1371-1:2011 shall be converted according to Annex A of the respective standard, if the new versions are applied.			
NOTE These safety factors assume testing for surface and volumetric flaws.			
^a Based on Table 6 values.			

7.5.7 Damage accumulation

The damage D shall be calculated according to the modified Miner's rule (Haibach 2006). It shall be less than or equal to unity as per Formula (5) and IEC 61400-1:2019.

$$D = \sum_{i=1} D_i = \sum_{i=1} \frac{n_i}{N_i} \leq 1 \quad (5)$$

where n_i is the number of cycles in bin " i " and N_i is the number of cycles on the S-N curve corresponding to the stress amplitude of bin " i " according to Figure 3.

The load-reserve factor for fatigue RRF_f expresses the fatigue strength of the structural component.

The general procedure of the fatigue analysis using the Miner's rule is summarized in IEC 61400-1:2019, Annex H. Guidance of calibration of partial safety factors is provided in Annex C.

7.5.8 Bolted joints

The nominal stress approach shall be used, with both normal and bending stresses taken into account. Generally, the 1st free thread is the critical area and both bolt ends shall be analyzed.

Fatigue calculations shall be carried out with minimal assumed value of preload due to embedding, tightening method, recovery losses, losses from plastic overstretching, etc. Additionally, non-linear behaviour (e.g. due to gaps or rolling bearing behaviour) shall be taken into account.

S-N curves may be found in standards such as VDI 2230-1, EN 1993-1-9 with dependence on the diameter, the type of coating and the manufacturing process (e.g. rolls) included. Such boundary conditions have an influence on the endurance limit and the curve slope, and therefore shall be considered. Where needed, S-N curves should be formulated for variable amplitude loading and consideration of cut-off limits is not allowed.

Care shall be taken if SN-curves for large bolt diameters (> M39) are taken from guidelines, especially VDI 2230-1. SN curves may also be derived from tests, based for example on ISO 3800. Damage should be calculated in accordance with 7.5.7.

7.5.9 Fibre reinforced material

The fatigue strength of parts from fibre reinforced materials shall be verified according to IEC 61400-5 or an equivalent standard.

7.6 Fracture mechanics assessment

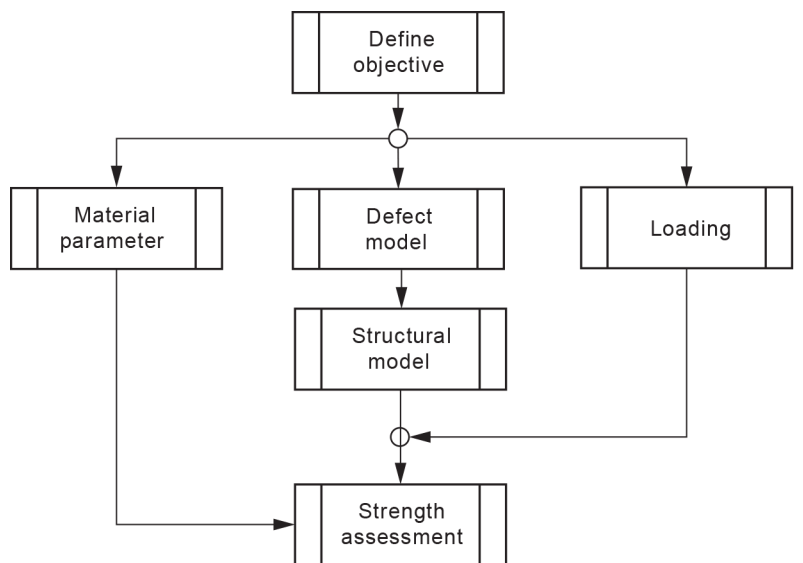
7.6.1 General

Static and fatigue strength assessment is based on the assumption of a perfect material composition. In case of brittle failure or other applications as mentioned in 7.6.2, it is necessary to investigate the load-carrying capabilities of metallic structural components of the nacelle with pre-existing or assumed cracks. The following steps may be followed.

Brittle material shall be assumed when the rupture strain is less than 12 % at the lowest operational temperature of the non-welded material and when the criteria according to EN 1993-1-10 are not fulfilled for welded components. Further information about the behaviour of components and systems in cold environment may be taken from VDMA 23901 [11].

The general process of a fracture mechanics calculation is shown in Figure 4. Further guidance may be taken from other guidelines and standards like BS 7910, the FKM Guideline (FKM–RBM-04-18) and VDMA 23902 (for planet carriers) for fracture mechanics assessment. For gearbox structures, the fracture mechanical verification may be omitted when an additional safety factor for static and fatigue strength is verified to be at least 1,5.

The crack opening mode I / tensile mode is representative for most applications and considered exemplarily in the following steps.



IEC

Figure 4 – Fracture mechanics calculation – process flow chart

7.6.2 Define objective

The basis for every fracture mechanics calculation is the assumption of an imperfect material including defects.

Possible reasons for crack initiation or crack shaped defects in materials are for example:

- defects due to manufacturing process,
- defects due to structural loading – crack growth.

The following objectives are characteristic for fracture mechanics calculations:

- life assessment,
- validation of permissible defects, e.g. out of cast/weld quality classes,
- evaluation of detected or possible material defects/damage tolerance and transferring findings to crack lengths according to FKM Guideline on fracture mechanics or BS 7910,
- prediction of crack growth,
- quality management/inspection interval for pre-existing cracks.

To perform the assessment, one of the available fracture mechanics assessment concepts shall be chosen. The most common ones are:

- linear elastic fracture mechanics (LEFM),
- elastic plastic fracture mechanics (EPFM).

Other concepts may also be applicable.

7.6.3 Material parameter

For the calculation of the static limit, in general the following parameters are needed:

- Fracture/material toughness, i.e. for mode I (tensile mode) and LEFM, K_{IC} / K_{mat}

For the calculation of the crack growth behaviour, the propagation rate parameters are the following for the Paris-Erdogan equation:

- C , n and threshold value ΔK_{th}

If alternative or modified methods are used, other parameters could be needed to calculate the propagation rate.

Material properties shall be derived from material codes or standardized material tests, e.g. in accordance with ISO 12108, ISO 12135 or an equivalent standard, by using specimens that are representative of the assessed component.

For the elastic-plastic fracture mechanics, the crack tip opening includes the local plasticity and is described by the J-Integral. The main focus is the advanced assessments of small cracks of ductile materials using numerical methods. The FKM Guideline fracture mechanics may be used for further guidance.

7.6.4 Defect model

A defect model is required to substitute the geometrical dimension of the defect/crack as well as the surrounding structure. Based on these models, the stress intensity factor K is determined as the loading parameter for brittle fracture (static) and crack growth (cyclic/dynamic).

Related to the objective of a fracture mechanics calculation, see 7.6.2, the relevant areas of the assessed structural component are defined, and adequate defect models are set up.

For analytical calculation models, defects/cracks are classified as follows and shown in Figure 5:

- surface cracks,
- embedded cracks,
- continuous/through cracks.

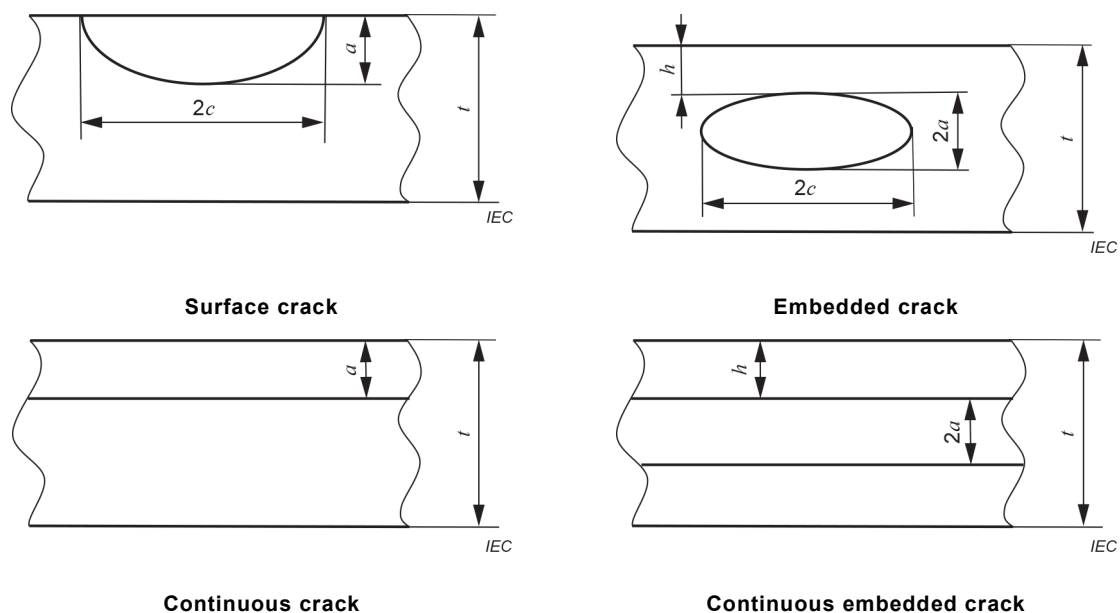


Figure 5 – Idealized crack types

The size and orientation of inner and surface defects can be detected by adequate methods, e.g. by using past data from similar component designs and testing methods or with the guidance of standards. Defects related to the manufacturing quality (e.g. cast quality, weld quality, etc.) may be quantified by non-destructive testing methods. The individual crack shape and dimensions are transferred to a crack model. For examples, refer to BS 7910 or the FKM Guideline on fracture mechanics. They include:

- crack depth a ,
- crack length c .

The " a " and " c " parameters should be determined using appropriate NDT methods in combination with the above-mentioned standards. For embedded cracks, the position of the crack in relation to the surface should be considered. For actual cracks, the crack position is derived out of non-destructive testing methods. Further guidance on how to determine the crack length out of material testing methods is given in e.g. FKM Guideline on fracture mechanics.

Due to the manufacturing process, possible defects can vary in size depending on the assumed location, e.g. for cast material in the transitory/core zone according to EN 12680-3 or for welded materials in the heat affected zone. The fracture mechanics assessment for assumed defects shall consider all relevant regions separately.

7.6.5 Structural model

For the static and cyclic fracture mechanics assessment, a structural model is required in combination with a defect model, see 7.6.4, to derive the resultant loading for fracture mechanics.

The structural model is oriented to the shape and dimensions of the defect surrounding structure. Standardized structural models like plate, cylinder or round bar can be found in the FKM Guideline on fracture mechanics.

For a more detailed analysis, the crack may be modelled by using numerical methods like FEA. In this case, the stress intensity factor K at the crack tip is derived out of the FE analysis. Specific meshing requirements in the crack region shall be observed as satisfying the principles of fracture mechanics.

7.6.6 Loading

The local loading of the crack tip depends on the structural loading as well as the crack shape and orientation. The structural loading is equivalent to the application of loads as referenced in Clause 5 and shall include the partial safety factor for loads γ_f in accordance with IEC 61400-1:2019.

The characteristic parameter for the LEFM is the stress intensity factor K at the crack tip for different crack opening modes. In the LEFM approach, elastic material behaviour is assumed while determining the critical stress (VDMA 23902).

To determine the stress intensity factor K , the structural loading, as a result of numerical or analytical calculation, shall be transferred to the fracture mechanics substitute model. For the static strength assessment, the highest stress from the critical crack opening situation shall be evaluated.

Depending on the crack position, a stress path through the wall thickness is considered to determine the nonlinear stress distribution. If the stress distribution is linearized across the cross-section, this shall be done in a conservative manner in accordance with the FKM Guideline on fracture mechanics or BS 7910.

The ultimate strength assessment and the cyclic loading leading to crack propagation shall consider the same load channels which would also be used for a static and fatigue strength assessment of the unflawed structure. The mean stress influence shall be considered by adequate means.

7.6.7 Strength assessment

7.6.7.1 Static limit state

The ultimate strength limit state for crack opening mode I is defined as:

$$K_I \leq K_{\text{mat}} \quad (6)$$

With the stress intensity factor K_I defined as:

$$K_I = f(\text{crack length, stress, geometry}) \quad (7)$$

Safety factors for the stress intensity factor shall be calculated in accordance with the FKM Guideline on fracture mechanics or BS 7910.

To address the risk of plastic collapse, this may be done by a failure assessment diagram (FAD) to check if there is any risk of both brittle material failure and plastic collapse. A general example is given in Figure 6. Other methods may also be applicable.

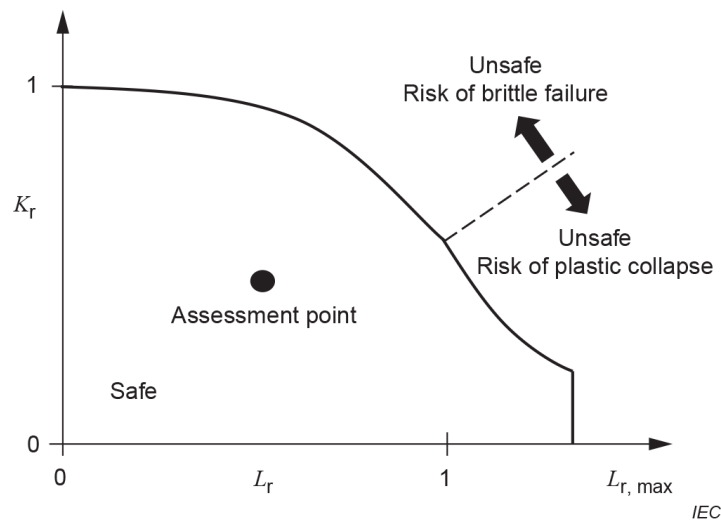


Figure 6 – Failure assessment diagram (FAD)

With

$$K_r = \frac{K_I}{K_{\text{mat}}} + \rho \quad (8)$$

And

$$L_r = \frac{\sigma_{\text{ref}}}{\sigma_Y} \quad (9)$$

where

K_I is the stress intensity factor;

K_{mat} is the corresponding material limit;

ρ is the plasticity interaction factor as defined in the FKM Guideline on fracture mechanics;

σ_{ref} is defined as the net section stress;

σ_Y is defined as the yield strength of the material according to BS 7910.

7.6.7.2 Fatigue limit state

The limit state function for dynamic crack growth shall be formulated as

$$a(t) < a_{crit} \quad (10)$$

where

$a(t)$ is the propagated crack growth;

a_0 is the initial crack length a ($t = 0$);

a_{crit} is the critical crack length/limiting crack depth (e.g. plate thickness).

The Paris-Erdogan equation is a method to compute the stable crack growth behaviour and can be formulated as:

$$\frac{da}{dN} = C(\Delta K)^n \quad (11)$$

Modified or alternative methods may also be applicable.

The correlation of the crack growth per load cycle da/dN and the cyclic stress intensity factor ΔK is shown in Figure 7.

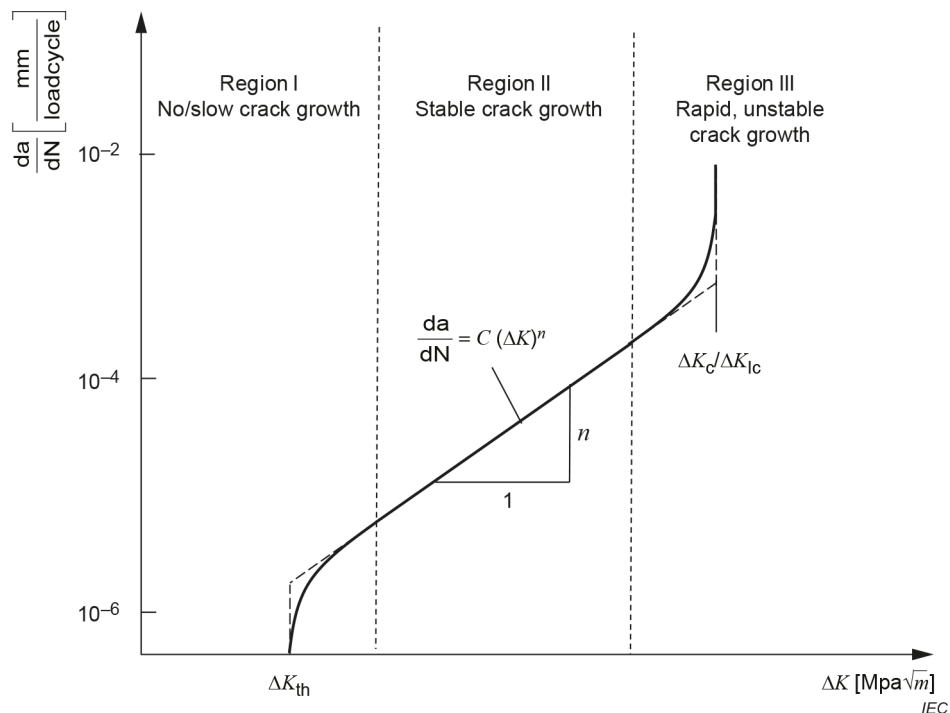


Figure 7 – Crack growth under cyclic loading by Paris/Erdogan

The lower threshold of the crack growth in region I, see Figure 7, is defined by ΔK_{th} . If the cyclic stress intensity factor ΔK is below this value, no crack propagation is initiated.

$$\Delta K \leq \Delta K_{th} \rightarrow \frac{da}{dN} = 0 \quad (12)$$

In all other cases, crack propagation is initiated. This leads to a more severe situation at the crack tip until the failure of the component, see Figure 8. If crack growth occurs, an assessment is required if this could lead to component collapse or to a limited continued operation of a wind turbine based on the remaining calculated lifetime. Furthermore, it shall be ensured that the component can still bear the specified static loads at any time.

For actual significant defects detected by non-destructive testing methods, it is required to check if an inspection interval on the wind turbine can be defined to validate the crack growth behaviour.

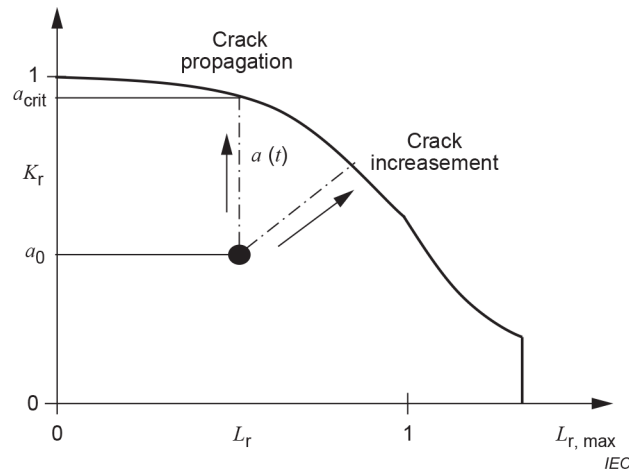


Figure 8 – Crack propagation and critical crack length in failure assessment diagram

As a conservative approach, the assessment shall start with the cyclic calculation to derive possible crack growth. The directional vector of the first principal stress of the identified most severe load case may be assumed as constant also for other load combinations in a simplified manner.

The calculated first principal stress as a function over time $\sigma_1(t)$ for each hotspot shall be processed with a Rainflow counting to calculate a stress collective including the number of occurrences of all meaningful stress load cycles. It shall be ensured that the most harmful events/extreme loads won't drive the existing or assumed cracks to lengths that will lead to instable fatigue crack growth during the remaining component lifetime. The consequent static assessment considers the propagated end crack length a_{end} .

Other means to calculate the loading at the crack tip may also be applicable.

7.7 Fracture mechanics-based design

The current practice of component design is to stay below the safe life boundary of the S/N-curve whereas the fracture mechanics approach allows the utilization of the fail-safe region. Therefore, it is possible to integrate a fracture mechanics-based design approach into the fatigue limit state procedure, see 7.5 and BS 7910:2013, Annex K giving information on the use of structural reliability methods, test results and relationship to partial safety factors.

However, this approach may be treated as a supplemental verification and not supersede the static and fatigue strength assessment which are referenced in this document.

This requires information regarding all relevant parameters needed for the fracture mechanics assessment and following an applicable law for crack growth (e.g. Paris-Erdogan equation) as the probabilistic fatigue crack growth is related to uncertainties. The most severe uncertainties are related to:

- fracture toughness of the material K_{mat} ,
- crack propagation rate parameters,
- size, distribution and position of flaws,
- time dependent loading at areas of interest.