IEC 61400-6

Edition 1.1 2025-06
CONSOLIDATED VERSION

INTERNATIONAL STANDARD

Wind energy generation systems –
Part 6: Tower and foundation design requirements

ICS 27.180

ISBN 978-2-8327-0510-0

IEC 61400-6:2020-04+AMD1:2025-06 CSV(en)

CONTENTS

FOREWORD 9
INTRODUCTION 11
INTRODUCTION to Amendment 1 11
1 Scope 12
2 Normative references 12
3 Terms and definitions 13
4 Symbols and abbreviated terms 18
4.1 Symbols 18
4.2 Abbreviated terms 25
5 Design basis including loading 25
5.1 General 25
5.2 Basis of design 26
5.2.1 Basic principles 26
5.2.2 Durability 26
5.2.3 Principles of limit state design 26
5.2.4 Structural analysis 27
5.2.5 Assessments by tests 27
5.3 Materials 27
5.4 Loads 28
5.4.1 Use of IEC 61400-1 or IEC 61400-2 load cases and partial safety factors for loads 28
5.4.2 Superseding of IEC 61400-1 or IEC 61400-2 partial safety factors for materials 28
5.4.3 Serviceability load levels 28
5.4.4 Load combinations in ULS 29
5.4.5 Structural damping values to be used in load calculations 30
5.4.6 Definitions and methods for use of internal loads 30
5.4.7 Definition of required load data for fatigue analysis 31
5.4.8 Definition of required load data for extreme load level 31
5.4.9 Vortex induced vibration 31
5.4.10 Loads due to geometric tolerances and elastic deflections in tower verticality 32
5.5 Load data and interface reporting requirements 32
5.5.1 Purpose 32
5.5.2 Wind turbine specification 32
5.5.3 Time history data 33
5.5.4 Load origins 33
5.5.5 Load components 33
5.6 General structural design requirements 34
5.6.1 Secondary structural influence 34
5.6.2 Fatigue analysis 34
5.7 Delivery documentation 34
6 Steel towers 34
6.1 General 34
6.2 Basis of design 34
6.3 Materials 34
6.3.1 General 34

6.3.2 Structural steels 34
6.3.3 Bolts and anchors 37
6.4 Ultimate strength analysis for towers and openings 38
6.4.1 General 38
6.4.2 Partial safety factors 38
6.4.3 Verification of ultimate strength 39
6.4.4 Tower assessment 39
6.4.5 Detail assessments 39
6.5 Stability 40
6.5.1 General 40
6.5.2 Partial safety factor 40
6.5.3 Assessment 40
6.5.4 Door frames/stiffeners 41
6.6 Fatigue limit state 41
6.6.1 General 41
6.6.2 Partial safety factor for materials 42
6.6.3 Assessment 42
6.6.4 Details 42
6.7 Ring flange connections 43
6.7.1 General 43
6.7.2 Design assumptions and requirements~~, execution of ring flanges~~ 43
6.7.3 Execution of ring flanges 45
~~6.7.4 Fatigue limit state analysis of bolted connection .....~~
6.7.4 Ultimate limit state analysis of flange and bolted connection 51
6.7.5 Fatigue limit state analysis of flange bolts 53
6.7.6 Fatigue limit state analysis of flange weld and fillet radius 62
6.8 Bolted connections resisting shear through friction 63
6.8.1 General requirements 63
6.8.2 Test-assisted design 64
6.8.3 Design without test 65
7 Concrete towers and foundations 66
7.1 General 66
7.2 Basis of design 66
7.2.1 Reference standard for concrete design 66
7.2.2 Partial safety factors 66
7.2.3 Basic variables 67
7.3 Materials 69
7.4 Durability 69
7.4.1 Durability requirements 69
7.4.2 Exposure classes 69
7.4.3 Concrete cover 69
7.5 Structural analysis 69
7.5.1 Finite element analysis 69
7.5.2 Foundation slabs 70
7.5.3 Regions with discontinuity in geometry or loads 70
7.5.4 Cast in anchor bolt arrangements 71
7.6 Concrete to concrete joints 71
7.7 Ultimate limit state 71
7.7.1 General 71

7.7.2 Shear and punching shear 72
7.8 Fatigue limit state 72
7.8.1 General 72
7.8.2 Reinforcement and prestressing steel fatigue failure 72
7.8.3 Concrete fatigue failure 72
7.9 Serviceability limit state 73
7.9.1 Load dependent stiffness reduction 73
7.9.2 Stress limitation 73
7.9.3 Crack control 73
7.9.4 Deformations 74
7.10 Execution 74
7.10.1 General 74
7.10.2 Requirements 74
7.10.3 Inspection of materials and products 74
7.10.4 Falsework and formwork 74
7.10.5 Reinforcement and embedded steel 74
7.10.6 Pre-stressing 74
7.10.7 Precast concrete elements 75
7.10.8 Geometrical tolerances 75
8 Foundations – Geotechnical design 75
8.1 General 75
8.2 Basis of design 75
8.2.1 General 75
8.2.2 Geotechnical limit states 76
8.3 Geotechnical data 76
8.3.1 General 76
8.3.2 Specific considerations 78
8.4 Supervision, monitoring and maintenance of construction 79
8.5 Gravity base foundations 79
8.5.1 General 79
8.5.2 Ultimate limit state (ULS) 80
8.5.3 Serviceability limit state (SLS) 83
8.6 Piled foundations 85
8.6.1 General 85
8.6.2 Pile loads 85
8.6.3 Ultimate limit state 86
8.6.4 Serviceability limit state 87
8.7 Rock anchored foundations 88
8.7.1 General 88
8.7.2 Types of rock anchor foundation 88
8.7.3 Geotechnical data 88
8.7.4 Corrosion protection 88
8.7.5 Anchor inspection and maintenance 89
8.7.6 Post tension tolerances and losses 89
8.7.7 Ultimate limit state 89
8.7.8 Serviceability limit state 90
8.7.9 Robustness check 90
8.7.10 Rock anchor design 91
9 Operation, service and maintenance requirements 93

9.1 Operation, maintenance and monitoring 93
9.2 Periodic structural inspections 93
9.3 Embedded steel structural section inspections 94
9.4 Bolt tension maintenance 94
9.5 Structural health monitoring 94
Annex A (informative) List of suitable design codes and guidelines for the calculation basis 95
A.1 General 95
A.2 Reference documents 95
Annex B (informative) List of material for structural steel 96
B.1 General 96
B.2 Structural steel 96
Annex C (informative) Bolts 97
C.1 General 97
C.2 Reference documents 98
C.3 Use of HV bolt assemblies 98
C.4 Water immersion test 99
Annex D (informative) Z-values for structural steel 100
D.1 General 100
D.2 Definition of Z-value according to Eurocode 100
D.3 Reference documents 100
Annex E (informative) Simplified buckling verification for openings in tubular steel towers 101
Annex F (informative) Fatigue verification 104
F.1 General 104
F.2 Specific details 104
Annex G (informative) Methods for ring flange verification 105
G.1 Method for ultimate strength analysis according to Petersen/Seidel 105
G.1.1 Basics 105
G.1.2 Calculation method 105
G.1.3 Extension by Tobinaga and Ishihara 109
G.2 Method for fatigue strength analysis according to ~~Schmidt/Neuper~~ Seidel 110
~~G.2.1 Basics ..... 110~~
~~G.2.2 Formulas for the tri-linear approximation ..... 110~~
G.2.1 Conditions for calculation model 112
G.2.2 Bolt force curve 113
G.2.3 Bolt moment curve 120
G.2.4 Calculation of force required to close inclination 121
G.3 Reference documents 122
Annex H (informative) Crack control – Guidance on 7.9.3 124
H.1 General 124
H.2 Crack control based on Eurocode 2 124
H.3 Crack control based on Japanese standards 124
H.4 Crack control based on ACI 318 125
H.5 Reference documents 125
Annex I (informative) Finite element analysis for concrete 126
I.1 General 126
I.2 Order and type of elements 126

I.3 Constitutive modelling 127
I.4 Solution methods 127
I.5 Implicit approach 127
I.6 Steps in conducting of a finite element analysis 128
I.7 Checking results 128
I.8 Reference documents 129
Annex J (informative) Tower-foundation anchorage 130
J.1 General 130
J.2 Embedded anchorages 130
J.3 Bolted anchorages 131
J.4 Grout 131
J.5 Anchor bolts 131
J.6 Embedded ring 131
J.7 Anchorage load transfer 132
Annex K (informative) Strut-and-tie section 133
K.1 General 133
K.2 Example of a rock anchor foundation 134
K.3 Reference documents 137
Annex L (informative) Guidance on selection of soil modulus and foundation rotational stiffness 139
L.1 General 139
L.2 Soil model 139
L.3 Dynamic rotational stiffness 141
L.4 Static rotational stiffness 142
L.5 Reference documents 143
Annex M (informative) Guidance for rock anchored foundation design 144
M.1 General 144
M.2 Corrosion protection 144
M.2.1 Standard anchors 144
M.2.2 Corrosion protection of bar anchors 145
M.3 Product approval 146
M.4 Rock anchor design 146
M.5 Grout design 146
M.6 Testing and execution 146
M.7 Suitability/performance test 147
M.8 Acceptance/proof test 147
M.9 Supplementary extended creep tests 147
M.10 Reference documents 147
Annex N (informative) Internal loads – Explanation of internal loads 148
Annex O (informative) Seismic load estimation for wind turbine tower and foundation 150
O.1 General 150
O.2 Vertical ground motion 150
O.3 Structure model 150
O.4 Soil amplification 151
O.5 Time domain simulation 152
O.6 Reference documents 152
Annex P (informative) Structural damping ratio for the tower of wind turbine 153
P.1 General 153

P.2 First mode structural damping ratio 153
P.3 Second mode structural damping ratio 154
P.4 Higher mode damping 154
P.5 Reference documents 155
Annex Q (informative) Guidance on partial safety factors for geotechnical limit states 156
Q.1 General 156
Q.2 Equilibrium 156
Q.3 Bearing capacity 156
Q.4 Sliding resistance 157
Q.5 Overall stability 157
Q.6 Reference documents 158
Bibliography 159

Figure 1 – Flange notations as an example of an L-flange 36
Figure 2 – Door opening geometry 41
~~Figure 3 – Flange gaps k in the area of the tower wall .....~~
~~Figure 4 – Bolt force as a function of wall force .....~~
~~Figure 5 – S-N curve for detail category 36 .....~~
Figure 8 – Bolt force F_S as a function of external force Z (including dead weight) 45
Figure 9 – Flange gaps with gap height k and gap length l_k at the tower wall and flange surface inclination α_S 45
Figure 10 – Illustration of parallel gaps and angular gaps 46
Figure 11 – Example for flatness measurement evaluation (D = 6 000 mm) 47
Figure 12 – Clarification of flatness values for the individual flange (u_{tol}) and resulting gap height after mating of two flanges (k) 48
Figure 13 – Schematic representation of $k_{limit,unloaded}$ and $k_{limit,loaded}$ 51
Figure 14 – Schematic representation for the correct shimming of an unacceptable gap 51
Figure 15 – Total settlement $f_{Z,tot}$ as function of DFT_{sbw} 56
Figure 16 – Coating thickness reference points 57
Figure 17 – Gap shape (L_{gap} = 2 000 mm / k_{design} = 1,0 mm) 60
Figure 18 – S-N-curve for bolts (examples M30 and M80 shown) 62
Figure 19 – Distance requirements for the flange weld in case fillet radius is not explicitly assessed 63
Figure 6 – Thermal effects around tower cross-section 67
Figure 7 – Illustration of rock anchor length 93
Figure E.1 – Circumferentially edge-stiffened opening 102
Figure E.2 – Definition of W_s and t_s according to JSCE 103
Figure G.1 – Simplification of system to segment model 105
Figure G.2 – Locations of plastic hinges for different failure modes 106
Figure G.3 – Geometric parameters 107
Figure G.6 – Location of plastic hinges for T-flanges 109
Figure G.4 – Modification factor $\boldsymbol{\lambda}$ for different $\boldsymbol{\alpha}$ [1] 110
Figure G.7 – Illustration of bolt force model (L- and T-flanges) 113
Figure K.1 – Example for the design of a deep beam using the strut-and-tie method 133

Figure K.2 – Simple shapes of strut-and-tie models 133
Figure K.3 – Three examples for carrying load in a deep beam 134
Figure K.4 – Strut-and-tie models for a rock-anchor foundation 136
Figure K.5 – Top tie reinforcement in a rock-anchor foundation 137
Figure L.1 – Example stress-strain relationship for soil 139
Figure L.2 – Loading and unloading behaviour of soil 140
Figure L.3 – Variation of shear modulus with soil strain 141
Figure L.4 – Reduction in rotational stiffness due to load eccentricity 142
Figure L.5 – Illustrative example of reduction in foundation rotational stiffness due to increasing load eccentricity 143
Figure M.1 – Section through rock and anchor 144
Figure M.2 – Typical anchor configuration with corrosion protection 145
Figure N.1 – Representation of internal loads 149
Figure O.1 – Structure model for response spectrum method 151
Figure P.1 – First mode damping ratio for the steel tower of wind turbine 154

~~Table 1 – Flange tolerances~~ .....

Table 3 – Flange tolerances 47
Table 2 – Summary of geotechnical limit states 76
Table B.1 – National and regional steel standards and types 96
Table C.1 – Comparison of bolt material in ISO 898-1, JIS B1186 and ASTM A490M-12 97
Table C.2 – Mean preload after installation 98
Table E.1 – Coefficients for Formula (E.3) 102
Table G.1 – Data points for external forces and bolt forces for determination of polynomial coefficients 115
Table H.1 – Limit value of crack width based on Japanese standards [1] 125
Table P.1 – Damping coefficients 153
Table Q.1 – Minimum partial safety factors for the equilibrium limit state (European and North American practice) 156
Table Q.2 – Minimum partial safety factors on for the equilibrium limit state (JSCE) 156
Table Q.3 – Minimum partial material and resistance factors for the bearing resistance limit state, ULS 157
Table Q.4 – Minimum partial material and resistance factors for the sliding resistance limit state, ULS 157
Table Q.5 – Minimum partial material and resistance factors for the overall stability limit state, ULS 158

INTERNATIONAL ELECTROTECHNICAL COMMISSION

_____

WIND ENERGY GENERATION SYSTEMS –

Part 6: Tower and foundation design requirements

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.
3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.
4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.
5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.
6) All users should ensure that they have the latest edition of this publication.
7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.
8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.
9) IEC draws attention to the possibility that the implementation of this document may involve the use of (a) patent(s). IEC takes no position concerning the evidence, validity or applicability of any claimed patent rights in respect thereof. As of the date of publication of this document, IEC had not received notice of (a) patent(s), which may be required to implement this document. However, implementers are cautioned that this may not represent the latest information, which may be obtained from the patent database available at https://patents.iec.ch. IEC shall not be held responsible for identifying any or all such patent rights.

This consolidated version of the official IEC Standard and its amendment has been prepared for user convenience.

IEC 61400-6 edition 1.1 contains the first edition (2020-04) [documents 88/751/FDIS and 88/754/RVD], its corrigendum 1 (2020-11) and its amendment 1 (2025-06) [documents 88/1088/FDIS and 88/1096/RVD].

In this Redline version, a vertical line in the margin shows where the technical content is modified by amendment 1. Additions are in green text, deletions are in strikethrough red text. A separate Final version with all changes accepted is available in this publication.

International Standard IEC 61400-6 has been prepared by IEC technical committee TC 88: Wind energy generation systems.

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

FDIS	Report on voting
88/751/FDIS	88/754/RVD

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

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

Future standards in this series will carry the new general title as cited above. Titles of existing standards in this series will be updated at the time of the next edition.

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

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

INTRODUCTION

This document has been developed for the design of onshore wind turbine towers and foundations that will build on and complement the IEC 61400-1 relating to design criteria and provide a complete set of technical requirements for the structural and geotechnical design. The requirements are also applicable to wind turbines covered by IEC 61400-2. It is envisaged that the proposed work will be followed by the development of another part, directed towards the design of offshore support structures, thus also complementing IEC 61400-3-1.

Civil engineering practices associated with the scope of the standard have regional variations. It is not the intention of this document to conflict with those practices but to supplement them particularly in ensuring that all important features of typical wind turbine towers and foundations are fully and correctly considered. To this end, the relevant parts in existing standards for design of steel and concrete structures and for geotechnical design have been identified for participating countries and regions.

The principles included in this document apply to the sections of the tower of an offshore fixed structure above the splash zone if the loading has been calculated according to IEC 61400-3-1.

This document will include the evaluation and calibration of partial safety factors for material strengths to be used together with the safety elements in IEC 61400-1 and IEC 61400-2 for loads and for verification of static equilibrium.

INTRODUCTION to Amendment 1

Clauses and subclauses as given in this document are replacing or amending the respective clauses and subclauses of IEC 61400-6:2020. The main part of this amendment concerns updated knowledge for the design of L-flanges and modifications required due to changes to IEC 61400-1.

The previous method of fatigue assessment using the Schmidt/Neuper trilinear bolt force curve approximation has been removed as the default method from the document. It has been replaced with a physically more accurate method.

The updated methodology for fatigue assessment of L-flanges has been calibrated so that the target failure probability defined in IEC 61400-1 is achieved. Where existing flange designs are checked with the updated method, over-utilization can be found, which in some cases can show an order of magnitude higher than nominally acceptable damage.

This does not impose an immediate risk for the turbines affected, though, due to the following factors:

a) in most cases, such designs have significant conservatism in the fatigue loads assumed, e.g. due to the assumption of uni-directional wind combined with type class turbulence conditions,

b) experience shows that broken bolts are almost always found and replaced before a turbine collapses.

It is not necessary to re-assess existing flange designs using the new method. In cases where broken bolts are found in operating turbines, the affected flange should be checked with the new methodology. Based on the assessment results and the root causes analysis for the failure, further measures should be defined (e.g. shorter inspection intervals).

WIND ENERGY GENERATION SYSTEMS –

Part 6: Tower and foundation design requirements

1 Scope

This part of IEC 61400 specifies requirements and general principles to be used in assessing the structural integrity of onshore wind turbine support structures (including foundations). The scope includes the geotechnical assessment of the soil for generic or site specific purposes. The strength of any flange and connection system connected to the rotor nacelle assembly (including connection to the yaw bearing) are designed and documented according to this document or according to IEC 61400-1. The scope includes all life cycle issues that may affect the structural integrity such as assembly and maintenance.

The assessment assumes that load data has been derived as defined in IEC 61400-1 or IEC 61400-2 and using the implicit reliability level and partial safety factors for loads.

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 61400-1:2019/AMD1:2024

IEC 61400-2, *Wind turbines – Part 2: Small wind turbines*

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

ISO 898-1, *Mechanical properties of fasteners made of carbon steel and alloy steel – Part 1: Bolts, screws and studs with specified property classes – Coarse thread and fine pitch thread*

ISO 898-2, *Fasteners – Mechanical properties of fasteners made of carbon steel and alloy steel – Part 2: Nuts with specified property classes*

ISO 898-3, *Mechanical properties of fasteners made of carbon steel and alloy steel – Part 3: Flat washers with specified property classes*

ISO 965-2, ISO general purpose metric screw threads – Tolerances – Part 2: Limits of sizes for general purpose external and internal threads – Medium tolerance quality

ISO 965-5, ISO general purpose metric screw threads –Tolerances – Part 5: Limits of sizes for internal screw threads to mate with hot-dip galvanized external screw threads with maximum size of tolerance position h before galvanizing

ISO 4759-1, *Tolerances for fasteners – Part 1: Bolts, screws, studs and nuts – Product grades A, B and C*

ISO 4759-3, *Tolerances for fasteners – Part 3: Washers for bolts, screws and nuts – Product grades A, C and F*

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

ISO 22965-1, *Concrete – Part 1: Methods of specifying and guidance for the specifier*

ISO 22965-2, *Concrete – Part 2: Specification of constituent materials, production of concrete and compliance of concrete*

ISO 22966, *Execution of concrete structures*

ISO 6934 (all parts), *Steel for the prestressing of concrete*

ISO 6935 (all parts), *Steel for the reinforcement of concrete*

ISO 9016:2012, *Destructive tests on welds in metallic materials – Impact tests – Test specimen location, notch orientation and examination*

ISO 12944 (all parts), *Paints and varnishes – Corrosion protection of steel structures by protective paint systems*

EN 1993-1-9:2005, *Eurocode 3: Design of steel structures – Part 1-9: Fatigue*

EN 1993-3-2:2006, *Eurocode 3: Design of steel structures – Part 3-2: Towers, masts and chimneys – Chimneys*

CONTENTS

FOREWORD 9
INTRODUCTION 11
INTRODUCTION to Amendment 1 11
1 Scope 12
2 Normative references 12
3 Terms and definitions 13
4 Symbols and abbreviated terms 18
4.1 Symbols 18
4.2 Abbreviated terms 24
5 Design basis including loading 25
5.1 General 25
5.2 Basis of design 25
5.2.1 Basic principles 25
5.2.2 Durability 26
5.2.3 Principles of limit state design 26
5.2.4 Structural analysis 26
5.2.5 Assessments by tests 27
5.3 Materials 27
5.4 Loads 27
5.4.1 Use of IEC 61400-1 or IEC 61400-2 load cases and partial safety factors for loads 27
5.4.2 Superseding of IEC 61400-1 or IEC 61400-2 partial safety factors for materials 28
5.4.3 Serviceability load levels 28
5.4.4 Load combinations in ULS 29
5.4.5 Structural damping values to be used in load calculations 30
5.4.6 Definitions and methods for use of internal loads 30
5.4.7 Definition of required load data for fatigue analysis 30
5.4.8 Definition of required load data for extreme load level 31
5.4.9 Vortex induced vibration 31
5.4.10 Loads due to geometric tolerances and elastic deflections in tower verticality 31
5.5 Load data and interface reporting requirements 32
5.5.1 Purpose 32
5.5.2 Wind turbine specification 32
5.5.3 Time history data 33
5.5.4 Load origins 33
5.5.5 Load components 33
5.6 General structural design requirements 33
5.6.1 Secondary structural influence 33
5.6.2 Fatigue analysis 33
5.7 Delivery documentation 33
6 Steel towers 34
6.1 General 34
6.2 Basis of design 34
6.3 Materials 34
6.3.1 General 34

6.3.2 Structural steels 34
6.3.3 Bolts and anchors 37
6.4 Ultimate strength analysis for towers and openings 38
6.4.1 General 38
6.4.2 Partial safety factors 38
6.4.3 Verification of ultimate strength 38
6.4.4 Tower assessment 38
6.4.5 Detail assessments 38
6.5 Stability 39
6.5.1 General 39
6.5.2 Partial safety factor 39
6.5.3 Assessment 39
6.5.4 Door frames/stiffeners 40
6.6 Fatigue limit state 40
6.6.1 General 40
6.6.2 Partial safety factor for materials 41
6.6.3 Assessment 41
6.6.4 Details 41
6.7 Ring flange connections 42
6.7.1 General 42
6.7.2 Design assumptions and requirements 42
6.7.3 Execution of ring flanges 42
6.7.4 Ultimate limit state analysis of flange and bolted connection 49
6.7.5 Fatigue limit state analysis of flange bolts 49
6.7.6 Fatigue limit state analysis of flange weld and fillet radius 57
6.8 Bolted connections resisting shear through friction 59
6.8.1 General requirements 59
6.8.2 Test-assisted design 59
6.8.3 Design without test 61
7 Concrete towers and foundations 61
7.1 General 61
7.2 Basis of design 61
7.2.1 Reference standard for concrete design 61
7.2.2 Partial safety factors 61
7.2.3 Basic variables 62
7.3 Materials 64
7.4 Durability 64
7.4.1 Durability requirements 64
7.4.2 Exposure classes 64
7.4.3 Concrete cover 64
7.5 Structural analysis 65
7.5.1 Finite element analysis 65
7.5.2 Foundation slabs 65
7.5.3 Regions with discontinuity in geometry or loads 65
7.5.4 Cast in anchor bolt arrangements 66
7.6 Concrete to concrete joints 66
7.7 Ultimate limit state 67
7.7.1 General 67
7.7.2 Shear and punching shear 67

7.8 Fatigue limit state 67
7.8.1 General 67
7.8.2 Reinforcement and prestressing steel fatigue failure 67
7.8.3 Concrete fatigue failure 68
7.9 Serviceability limit state 68
7.9.1 Load dependent stiffness reduction 68
7.9.2 Stress limitation 68
7.9.3 Crack control 68
7.9.4 Deformations 69
7.10 Execution 69
7.10.1 General 69
7.10.2 Requirements 69
7.10.3 Inspection of materials and products 69
7.10.4 Falsework and formwork 69
7.10.5 Reinforcement and embedded steel 69
7.10.6 Pre-stressing 70
7.10.7 Precast concrete elements 70
7.10.8 Geometrical tolerances 70
8 Foundations – Geotechnical design 70
8.1 General 70
8.2 Basis of design 71
8.2.1 General 71
8.2.2 Geotechnical limit states 71
8.3 Geotechnical data 72
8.3.1 General 72
8.3.2 Specific considerations 73
8.4 Supervision, monitoring and maintenance of construction 74
8.5 Gravity base foundations 74
8.5.1 General 74
8.5.2 Ultimate limit state (ULS) 75
8.5.3 Serviceability limit state (SLS) 78
8.6 Piled foundations 80
8.6.1 General 80
8.6.2 Pile loads 80
8.6.3 Ultimate limit state 81
8.6.4 Serviceability limit state 82
8.7 Rock anchored foundations 83
8.7.1 General 83
8.7.2 Types of rock anchor foundation 83
8.7.3 Geotechnical data 83
8.7.4 Corrosion protection 83
8.7.5 Anchor inspection and maintenance 84
8.7.6 Post tension tolerances and losses 84
8.7.7 Ultimate limit state 84
8.7.8 Serviceability limit state 85
8.7.9 Robustness check 85
8.7.10 Rock anchor design 86
9 Operation, service and maintenance requirements 88
9.1 Operation, maintenance and monitoring 88

9.2 Periodic structural inspections 88
9.3 Embedded steel structural section inspections 89
9.4 Bolt tension maintenance 89
9.5 Structural health monitoring 89
Annex A (informative) List of suitable design codes and guidelines for the calculation basis 90
A.1 General 90
A.2 Reference documents 90
Annex B (informative) List of material for structural steel 91
B.1 General 91
B.2 Structural steel 91
Annex C (informative) Bolts 92
C.1 General 92
C.2 Reference documents 93
C.3 Use of HV bolt assemblies 93
C.4 Water immersion test 94
Annex D (informative) Z-values for structural steel 95
D.1 General 95
D.2 Definition of Z-value according to Eurocode 95
D.3 Reference documents 95
Annex E (informative) Simplified buckling verification for openings in tubular steel towers 96
Annex F (informative) Fatigue verification 99
F.1 General 99
F.2 Specific details 99
Annex G (informative) Methods for ring flange verification 100
G.1 Method for ultimate strength analysis according to Petersen/Seidel 100
G.1.1 Basics 100
G.1.2 Calculation method 100
G.1.3 Extension by Tobinaga and Ishihara 104
G.2 Method for fatigue strength analysis according to Seidel 105
G.2.1 Conditions for calculation model 105
G.2.2 Bolt force curve 106
G.2.3 Bolt moment curve 113
G.2.4 Calculation of force required to close inclination 114
G.3 Reference documents 115
Annex H (informative) Crack control – Guidance on 7.9.3 116
H.1 General 116
H.2 Crack control based on Eurocode 2 116
H.3 Crack control based on Japanese standards 116
H.4 Crack control based on ACI 318 117
H.5 Reference documents 117
Annex I (informative) Finite element analysis for concrete 118
I.1 General 118
I.2 Order and type of elements 118
I.3 Constitutive modelling 119
I.4 Solution methods 119
I.5 Implicit approach 119

I.6 Steps in conducting of a finite element analysis 120
I.7 Checking results 120
I.8 Reference documents 121
Annex J (informative) Tower-foundation anchorage 122
J.1 General 122
J.2 Embedded anchorages 122
J.3 Bolted anchorages 123
J.4 Grout 123
J.5 Anchor bolts 123
J.6 Embedded ring 123
J.7 Anchorage load transfer 124
Annex K (informative) Strut-and-tie section 125
K.1 General 125
K.2 Example of a rock anchor foundation 126
K.3 Reference documents 129
Annex L (informative) Guidance on selection of soil modulus and foundation rotational stiffness 131
L.1 General 131
L.2 Soil model 131
L.3 Dynamic rotational stiffness 133
L.4 Static rotational stiffness 134
L.5 Reference documents 135
Annex M (informative) Guidance for rock anchored foundation design 136
M.1 General 136
M.2 Corrosion protection 136
M.2.1 Standard anchors 136
M.2.2 Corrosion protection of bar anchors 137
M.3 Product approval 138
M.4 Rock anchor design 138
M.5 Grout design 138
M.6 Testing and execution 138
M.7 Suitability/performance test 139
M.8 Acceptance/proof test 139
M.9 Supplementary extended creep tests 139
M.10 Reference documents 139
Annex N (informative) Internal loads – Explanation of internal loads 140
Annex O (informative) Seismic load estimation for wind turbine tower and foundation 142
O.1 General 142
O.2 Vertical ground motion 142
O.3 Structure model 142
O.4 Soil amplification 143
O.5 Time domain simulation 144
O.6 Reference documents 144
Annex P (informative) Structural damping ratio for the tower of wind turbine 145
P.1 General 145
P.2 First mode structural damping ratio 145
P.3 Second mode structural damping ratio 146
P.4 Higher mode damping 146

P.5 Reference documents 147
Annex Q (informative) Guidance on partial safety factors for geotechnical limit states 148
Q.1 General 148
Q.2 Equilibrium 148
Q.3 Bearing capacity 148
Q.4 Sliding resistance 149
Q.5 Overall stability 149
Q.6 Reference documents 150
Bibliography 151

Figure 1 – Flange notations as an example of an L-flange 36
Figure 2 – Door opening geometry 40
Figure 8 – Bolt force F_S as a function of external force Z (including dead weight) 42
Figure 9 – Flange gaps with gap height k and gap length l_k at the tower wall and flange surface inclination α_S 43
Figure 10 – Illustration of parallel gaps and angular gaps 43
Figure 11 – Example for flatness measurement evaluation (D = 6 000 mm) 45
Figure 12 – Clarification of flatness values for the individual flange (u_{tol}) and resulting gap height after mating of two flanges (k) 45
Figure 13 – Schematic representation of $k_{limit,unloaded}$ and $k_{limit,loaded}$ 48
Figure 14 – Schematic representation for the correct shimming of an unacceptable gap 48
Figure 15 – Total settlement $f_{Z,tot}$ as function of DFT_{sbw} 51
Figure 16 – Coating thickness reference points 52
Figure 17 – Gap shape (L_{gap} = 2 000 mm / k_{design} = 1,0 mm) 55
Figure 18 – S-N-curve for bolts (examples M30 and M80 shown) 57
Figure 19 – Distance requirements for the flange weld in case fillet radius is not explicitly assessed 58
Figure 6 – Thermal effects around tower cross-section 62
Figure 7 – Illustration of rock anchor length 88
Figure E.1 – Circumferentially edge-stiffened opening 97
Figure E.2 – Definition of W_s and t_s according to JSCE 98
Figure G.1 – Simplification of system to segment model 100
Figure G.2 – Locations of plastic hinges for different failure modes 101
Figure G.3 – Geometric parameters 102
Figure G.6 – Location of plastic hinges for T-flanges 104
Figure G.4 – Modification factor $\boldsymbol{\lambda}$ for different $\boldsymbol{\alpha}$ [1] 105
Figure G.7 – Illustration of bolt force model (L- and T-flanges) 106
Figure K.1 – Example for the design of a deep beam using the strut-and-tie method 125
Figure K.2 – Simple shapes of strut-and-tie models 125
Figure K.3 – Three examples for carrying load in a deep beam 126
Figure K.4 – Strut-and-tie models for a rock-anchor foundation 128
Figure K.5 – Top tie reinforcement in a rock-anchor foundation 129
Figure L.1 – Example stress-strain relationship for soil 131

Figure L.2 – Loading and unloading behaviour of soil 132
Figure L.3 – Variation of shear modulus with soil strain..... 133
Figure L.4 – Reduction in rotational stiffness due to load eccentricity..... 134
Figure L.5 – Illustrative example of reduction in foundation rotational stiffness due to increasing load eccentricity..... 135
Figure M.1 – Section through rock and anchor 136
Figure M.2 – Typical anchor configuration with corrosion protection..... 137
Figure N.1 – Representation of internal loads 141
Figure O.1 – Structure model for response spectrum method..... 143
Figure P.1 – First mode damping ratio for the steel tower of wind turbine..... 146

Table 3 – Flange tolerances..... 44
Table 2 – Summary of geotechnical limit states 71
Table B.1 – National and regional steel standards and types 91
Table C.1 – Comparison of bolt material in ISO 898-1, JIS B1186 and ASTM A490M-12..... 92
Table C.2 – Mean preload after installation..... 93
Table E.1 – Coefficients for Formula (E.3) 97
Table G.1 – Data points for external forces and bolt forces for determination of polynomial coefficients..... 107
Table H.1 – Limit value of crack width based on Japanese standards [1] 117
Table P.1 – Damping coefficients..... 145
Table Q.1 – Minimum partial safety factors for the equilibrium limit state (European and North American practice)..... 148
Table Q.2 – Minimum partial safety factors on for the equilibrium limit state (JSCE) 148
Table Q.3 – Minimum partial material and resistance factors for the bearing resistance limit state, ULS 149
Table Q.4 – Minimum partial material and resistance factors for the sliding resistance limit state, ULS 149
Table Q.5 – Minimum partial material and resistance factors for the overall stability limit state, ULS 150

INTERNATIONAL ELECTROTECHNICAL COMMISSION

_____

WIND ENERGY GENERATION SYSTEMS –

Part 6: Tower and foundation design requirements

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.
3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.
4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.
5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.
6) All users should ensure that they have the latest edition of this publication.
7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.
8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.
9) IEC draws attention to the possibility that the implementation of this document may involve the use of (a) patent(s). IEC takes no position concerning the evidence, validity or applicability of any claimed patent rights in respect thereof. As of the date of publication of this document, IEC had not received notice of (a) patent(s), which may be required to implement this document. However, implementers are cautioned that this may not represent the latest information, which may be obtained from the patent database available at https://patents.iec.ch. IEC shall not be held responsible for identifying any or all such patent rights.

This consolidated version of the official IEC Standard and its amendment has been prepared for user convenience.

IEC 61400-6 edition 1.1 contains the first edition (2020-04) [documents 88/751/FDIS and 88/754/RVD], its corrigendum 1 (2020-11) and its amendment 1 (2025-06) [documents 88/1088/FDIS and 88/1096/RVD].

This Final version does not show where the technical content is modified by amendment 1. A separate Redline version with all changes highlighted is available in this publication.

International Standard IEC 61400-6 has been prepared by IEC technical committee TC 88: Wind energy generation systems.

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

FDIS	Report on voting
88/751/FDIS	88/754/RVD

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

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

Future standards in this series will carry the new general title as cited above. Titles of existing standards in this series will be updated at the time of the next edition.

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

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

INTRODUCTION

This document has been developed for the design of onshore wind turbine towers and foundations that will build on and complement the IEC 61400-1 relating to design criteria and provide a complete set of technical requirements for the structural and geotechnical design. The requirements are also applicable to wind turbines covered by IEC 61400-2. It is envisaged that the proposed work will be followed by the development of another part, directed towards the design of offshore support structures, thus also complementing IEC 61400-3-1.

Civil engineering practices associated with the scope of the standard have regional variations. It is not the intention of this document to conflict with those practices but to supplement them particularly in ensuring that all important features of typical wind turbine towers and foundations are fully and correctly considered. To this end, the relevant parts in existing standards for design of steel and concrete structures and for geotechnical design have been identified for participating countries and regions.

The principles included in this document apply to the sections of the tower of an offshore fixed structure above the splash zone if the loading has been calculated according to IEC 61400-3-1.

This document will include the evaluation and calibration of partial safety factors for material strengths to be used together with the safety elements in IEC 61400-1 and IEC 61400-2 for loads and for verification of static equilibrium.

INTRODUCTION to Amendment 1

Clauses and subclauses as given in this document are replacing or amending the respective clauses and subclauses of IEC 61400-6:2020. The main part of this amendment concerns updated knowledge for the design of L-flanges and modifications required due to changes to IEC 61400-1.

The previous method of fatigue assessment using the Schmidt/Neuper trilinear bolt force curve approximation has been removed as the default method from the document. It has been replaced with a physically more accurate method.

The updated methodology for fatigue assessment of L-flanges has been calibrated so that the target failure probability defined in IEC 61400-1 is achieved. Where existing flange designs are checked with the updated method, over-utilization can be found, which in some cases can show an order of magnitude higher than nominally acceptable damage.

This does not impose an immediate risk for the turbines affected, though, due to the following factors:

a) in most cases, such designs have significant conservatism in the fatigue loads assumed, e.g. due to the assumption of uni-directional wind combined with type class turbulence conditions,

b) experience shows that broken bolts are almost always found and replaced before a turbine collapses.

It is not necessary to re-assess existing flange designs using the new method. In cases where broken bolts are found in operating turbines, the affected flange should be checked with the new methodology. Based on the assessment results and the root causes analysis for the failure, further measures should be defined (e.g. shorter inspection intervals).

WIND ENERGY GENERATION SYSTEMS –

Part 6: Tower and foundation design requirements

1 Scope

This part of IEC 61400 specifies requirements and general principles to be used in assessing the structural integrity of onshore wind turbine support structures (including foundations). The scope includes the geotechnical assessment of the soil for generic or site specific purposes. The strength of any flange and connection system connected to the rotor nacelle assembly (including connection to the yaw bearing) are designed and documented according to this document or according to IEC 61400-1. The scope includes all life cycle issues that may affect the structural integrity such as assembly and maintenance.

The assessment assumes that load data has been derived as defined in IEC 61400-1 or IEC 61400-2 and using the implicit reliability level and partial safety factors for loads.

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 61400-1:2019/AMD1:2024

IEC 61400-2, *Wind turbines – Part 2: Small wind turbines*

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

ISO 898-1, *Mechanical properties of fasteners made of carbon steel and alloy steel – Part 1: Bolts, screws and studs with specified property classes – Coarse thread and fine pitch thread*

ISO 898-2, *Fasteners – Mechanical properties of fasteners made of carbon steel and alloy steel – Part 2: Nuts with specified property classes*

ISO 898-3, *Mechanical properties of fasteners made of carbon steel and alloy steel – Part 3: Flat washers with specified property classes*

ISO 965-2, ISO general purpose metric screw threads – Tolerances – Part 2: Limits of sizes for general purpose external and internal threads – Medium tolerance quality

ISO 965-5, ISO general purpose metric screw threads –Tolerances – Part 5: Limits of sizes for internal screw threads to mate with hot-dip galvanized external screw threads with maximum size of tolerance position h before galvanizing

ISO 4759-1, *Tolerances for fasteners – Part 1: Bolts, screws, studs and nuts – Product grades A, B and C*

ISO 4759-3, *Tolerances for fasteners – Part 3: Washers for bolts, screws and nuts – Product grades A, C and F*

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

ISO 22965-1, *Concrete – Part 1: Methods of specifying and guidance for the specifier*

ISO 22965-2, *Concrete – Part 2: Specification of constituent materials, production of concrete and compliance of concrete*

ISO 22966, *Execution of concrete structures*

ISO 6934 (all parts), *Steel for the prestressing of concrete*

ISO 6935 (all parts), *Steel for the reinforcement of concrete*

ISO 9016:2012, *Destructive tests on welds in metallic materials – Impact tests – Test specimen location, notch orientation and examination*

ISO 12944 (all parts), *Paints and varnishes – Corrosion protection of steel structures by protective paint systems*

EN 1993-1-9:2005, *Eurocode 3: Design of steel structures – Part 1-9: Fatigue*

EN 1993-3-2:2006, *Eurocode 3: Design of steel structures – Part 3-2: Towers, masts and chimneys – Chimneys*