INTERNATIONAL STANDARD

ISO 13823

First edition
2008-06-15

General principles on the design of structures for durability

Principes généraux du calcul des constructions pour la durabilité

Reference number
ISO 13823:2008(E)

PDF disclaimer

This PDF file may contain embedded typefaces. In accordance with Adobe's licensing policy, this file may be printed or viewed but shall not be edited unless the typefaces which are embedded are licensed to and installed on the computer performing the editing. In downloading this file, parties accept therein the responsibility of not infringing Adobe's licensing policy. The ISO Central Secretariat accepts no liability in this area.

Adobe is a trademark of Adobe Systems Incorporated.

Details of the software products used to create this PDF file can be found in the General Info relative to the file; the PDF-creation parameters were optimized for printing. Every care has been taken to ensure that the file is suitable for use by ISO member bodies. In the unlikely event that a problem relating to it is found, please inform the Central Secretariat at the address given below.

COPYRIGHT PROTECTED DOCUMENT

© ISO 2008

All rights reserved. Unless otherwise specified, no part of this publication may be reproduced or utilized in any form or by any means, electronic or mechanical, including photocopying and microfilm, without permission in writing from either ISO at the address below or ISO's member body in the country of the requester.

ISO copyright office
Case postale 56 • CH-1211 Geneva 20
Tel. + 41 22 749 01 11
Fax + 41 22 749 09 47
E-mail copyright@iso.org
Web www.iso.org

Published in Switzerland

Copyright International Organization for Standardization
Provided by IHS under license with ISO
No reproduction or networking permitted without license from IHS

Not for Resale

Contents

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

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

ISO 13823 was prepared by Technical Committee ISO/TC 98, *Bases for design of structures*, Subcommittee SC 2, *Reliability of structures*.

Introduction

The limit-states method, as developed in ISO 2394, has been adopted and used for preparing and harmonizing national and regional structural design standards and codes around the world. Although ISO 2394 includes durability in its principles, the limit-states method has not been developed for failures due to material deterioration to the extent that it has for failures due to actions such as gravity, wind, snow and earthquake. Also, many premature failures have occurred because of a lack of understanding of material deterioration in the structural engineering profession.

The first objective in developing this International Standard is to improve the evaluation and design of structures for durability by the incorporation of building-science principles into structural-engineering practice. These principles are now being taught in engineering courses in many countries. This goal is achieved by the incorporation of these principles into the limit-states method currently used in structural engineering practice and defined in ISO 2394, and by the use of a common, user-friendly terminology for physical phenomena.

Developments have recently taken place in mathematical modelling of the mechanisms that cause material deterioration and failure. There is a need to harmonize the use of these models in practice by using the limit-states method and a common terminology.

The second objective in developing this International Standard is to provide a framework for the development of mathematical models to predict the service life of components of the structure. Such models are currently being developed, for example, for concrete slabs subjected to chloride diffusion from de-icing salts. These models are material-dependent and, therefore, are being developed by other ISO/TCs. The goal of this International Standard is to ensure that all analytical models are incorporated into the limit-states method, the same as currently used for the verification and design of structures for gravity, wind, snow and earthquake actions.

While this International Standard does not address design procedures for durability, it lays a solid foundation by identifying a process starting from the structure’s environment, followed by mechanisms that transfer this environment into environmental actions on component materials leading to action effects, such as damage (see Figure 1). It is necessary to take this cause-and-effect process into account in developing methods for the prediction of service life.

This International Standard is intended to serve a similar unification role as ISO 2394 has had over the past 30 years for the verification and design of structures against failure due to mechanical actions, such as gravity, wind, snow and earthquake.

This International Standard does not directly address sustainability for structures, except through referencing in notes in 8.4 and Clause 10. Most considerations of sustainability, such as the choice of material as it affects waste and energy consumption, are outside the scope of this International Standard. Sustainability considerations in the future, however, are expected to increase the emphasis on choice of materials, technologies, inspectability, maintenance, repair and replacement in the planning and design of structures.

It is intended that this International Standard be used in parallel with ISO 15686 (all parts) on service-life planning for buildings and construction assets. Service-life prediction for structures based on experience and testing are contained in ISO 15686 (all parts). Service-life prediction of structures based on the modelling of durability, in addition to experience and testing, using conceptual as well as mathematical models, are described in this International Standard.

INTERNATIONAL STANDARD **ISO 13823:2008(E)**

General principles on the design of structures for durability

1 Scope

This International Standard specifies general principles and recommends procedures for the verification of the durability of structures subject to known or foreseeable environmental actions, including mechanical actions, causing material degradation leading to failure of performance. It is necessary to ensure reliability of performance throughout the design service life of the structure.

Fatigue failure due to cyclic stress is not within the scope of this International Standard.

NOTE Reference can be made to ISO 2394 for failure due to fatigue.

2 Normative references

The following referenced documents are indispensable for the application 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.

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

ISO 3898:1997, *Bases for design of structures — Notations — General symbols*

ISO 8930:1987, *General principles on reliability for structures — List of equivalent terms*

ISO 13822:2001, *Bases for design of structures — Assessment of existing structures*

ISO 15686-5, *Buildings and constructed assets — Service-life planning — Part 5: Life-cycle costing*

ISO 15686-6, *Buildings and constructed assets — Service life planning — Part 6: Procedures for considering environmental impacts*

AS 5604, *Timber — Natural durability ratings*

3 Terms and definitions

3.1
action effect
S
effect of an environmental action on a component of a structure (e.g. damage, reduced resistance, internal force, displacement, change in appearance)

3.2
agent
chemical or biological substance or physical process (e.g. UV) or biological (e.g. insect attack) process that, alone or together with other agents, including contaminants in the material itself, acts on a structure or component to cause material degradation

3.3
basic variable
variable describing the structure environment, transfer mechanism, environmental action, action effect, material property or geometrical quantity

3.4
characteristic value of a basic variable
specified fractile of the variable determined in accordance with ISO 2394

3.5
characteristic service life
value of a predicted service life chosen either on a statistical basis, so that it has a specified probability of being more unfavourable (i.e. lower), or on a non-statistical basis, for instance based on acquired experience

3.6
component
any part of the structure and any non-structural part that may affect the durability of the structure

3.7
degradation
material deterioration or deformation that leads to adverse changes in a critical property of a component

3.8
design value of a basic variable
factored characteristic value of the variable determined in accordance with ISO 2394

3.9
design life
specified period of time for which a structure or a component is to be used for its intended purpose without major repair being necessary

NOTE This term is equivalent to **design working life** in ISO 2394:1998, 2.2.15.

3.10
durability
capability of a structure or any component to satisfy, with planned maintenance, the design performance requirements over a specified period of time under the influence of the environmental actions, or as a result of a self-ageing process

3.11
environmental action
chemical, electrochemical, biological, physical and/or mechanical action causing material degradation of a component

NOTE 1 See Figure 1.

NOTE 2 See also environmental influences in ISO 2394:1998, 6.3.

3.12
failure
loss of the ability of a structure or component to perform a specified function

3.13
initiation limit state
ILS
state that corresponds to the initiation of significant deterioration of a component of the structure

NOTE See 6.6.

3.14
limit state
state beyond which a structure or component no longer satisfies the design performance requirements

3.15
maintenance
combination of all technical and associated administrative actions during a component's **service life** (3.21) with the aim of retaining it in a state in which it can perform its required functions

3.16
model
simplified conceptual or mathematical idealization or test set-up simulating the structure environment, transfer mechanisms, environmental action, action effects and structural behaviour that can lead to failure

NOTE See Figure 1.

3.17
partial factor method
calculation format in which allowance is made for the uncertainties and variabilities of the basic variables by means of characteristic values, partial factors and, if relevant, additive quantities

3.18
predicted service life
service life (3.21) estimated from recorded performance, previous experience, tests or modelling

3.19
reliability
ability of a structure or component to satisfy the specified design performance requirements within the design service life

3.20
repair
restoration of a structure or its components to an acceptable condition by the renewal or replacement of worn, damaged or deteriorated components

3.21
service life
actual period of time during which a structure or any of its components satisfy the design performance requirements without unforeseen major repair

3.22
serviceability limit state
SLS
state that corresponds to conditions beyond which specified serviceability requirements for a structure or its components are no longer satisfied

NOTE See 6.6.

3.23
structure environment
external or internal influences (e.g. rain, de-icing salts, UV, humidity) on a structure that can lead to an environmental action

NOTE See Figure 1.

3.24
transfer mechanism
mechanism by which influences in the structure environment are, over time, transferred into agents on and within components or prevent such transfer

NOTE See Figure 1.

3.25
ultimate limit state
ULS
state associated with collapse, or with other similar forms of structural failure

NOTE See 6.6.

4 Symbols

P	probability
P_f	probability of failure
P_target	target probability of failure
$P_\mathrm{target,SLS}$	target probability of failure, serviceability limit state
$P_\mathrm{target,ULS}$	target probability of failure, ultimate limit state
R	resistance
$\overline{R}$	mean resistance
S	action effect
$\overline{S}$	mean action effect
S_lim	serviceability limit
t	time, expressed in years
t_D	design life, expressed in years
t_exposed	time after initiation of degradation, expressed in years
t_ref	reference service life, expressed in years; see 9.3.2
t_S	service life, expressed in years, that occurs or that is represented by a mathematical probability function
t_Sk	characteristic value of t_S, expressed in years
t_SP	predicted service life, expressed in years
t_start	time to initiation of degradation, expressed in years
X_i	basic variable for modelling t_start, S and R
Y_i	basic variable for modelling t_exposed, S and R
γ_S	partial factor for predicted service life; see Equation (4)

5 Application

It is the intention that the general principles in the verification and design of structures and components for durability in this International Standard be used whenever a minimum service life is required, for new structures as well as for the assessment of existing structures.

The considered components include non-structural components that can affect the durability of the structure.

NOTE Because of the complex nature of the degradation and damage of structures, durability of structures is related not only to structural components but also to non-structural components. However, non-structural components, such as equipment, are generally not included in this International Standard because they are normally easily replaced.

The general principles apply to the design phase as well as to planning maintenance, repair and replacement measures, in failure investigations, etc. However, additional considerations can apply to existing structures.

For existing structures, procedures and criteria in this International Standard may be modified to take into account inspection and test results concerning the quality of workmanship, conditions of maintenance and variation in the durability of materials. In addition, if they can be justified (see ISO 13822), lower target reliability levels may be used for existing structures.

6 Basic concepts for verifying durability

6.1 General

This International Standard recommends the use of the limit-states method shown in Figure 1 for the design and verification of structures for durability. For any component of the structure, this requires an understanding of the structure environment (6.2), the transfer mechanisms (6.3), the environmental action (6.4), leading to action effects (6.5) that can result in the failure of the component.

For examples of the application of the limit-states method in Figure 1, see Annex A.

NOTE Environmental action can also occur as the result of a self-ageing process (see 6.3, Note 3).

6.2 Structure environment

The structure environment contains influences, such as air, rain, contaminants, temperature, biological life and solar radiation, that provide agents such as moisture and oxygen that can affect the durability of components. These influences occur outside (climate, ground or body of water) or inside (climate, chemicals) the structure.

For examples of influences in the structure environment, see Annex B.

6.3 Transfer mechanisms

Transfer mechanisms, such as gravity, condensation and drainage, promote or prevent transfer of environmental influences into agents causing environmental action on or within the components of the structural system.

For examples of transfer mechanisms, see Annex C.

NOTE 1 Modelling of the deterioration process requires an understanding of the transfer mechanisms and environmental actions leading to failure. These are based on knowledge of the materials of the components and the microclimate in the vicinity of the component~~s~~ of the structure.

NOTE 2 Moisture, with or without contaminants, is the most important agent causing premature deterioration. The application of building science principles permits the generation of models — conceptual, mathematical or test set-up — for predicting the mechanisms, paths, volumes and forms of moisture that components are required to accommodate and to resist.

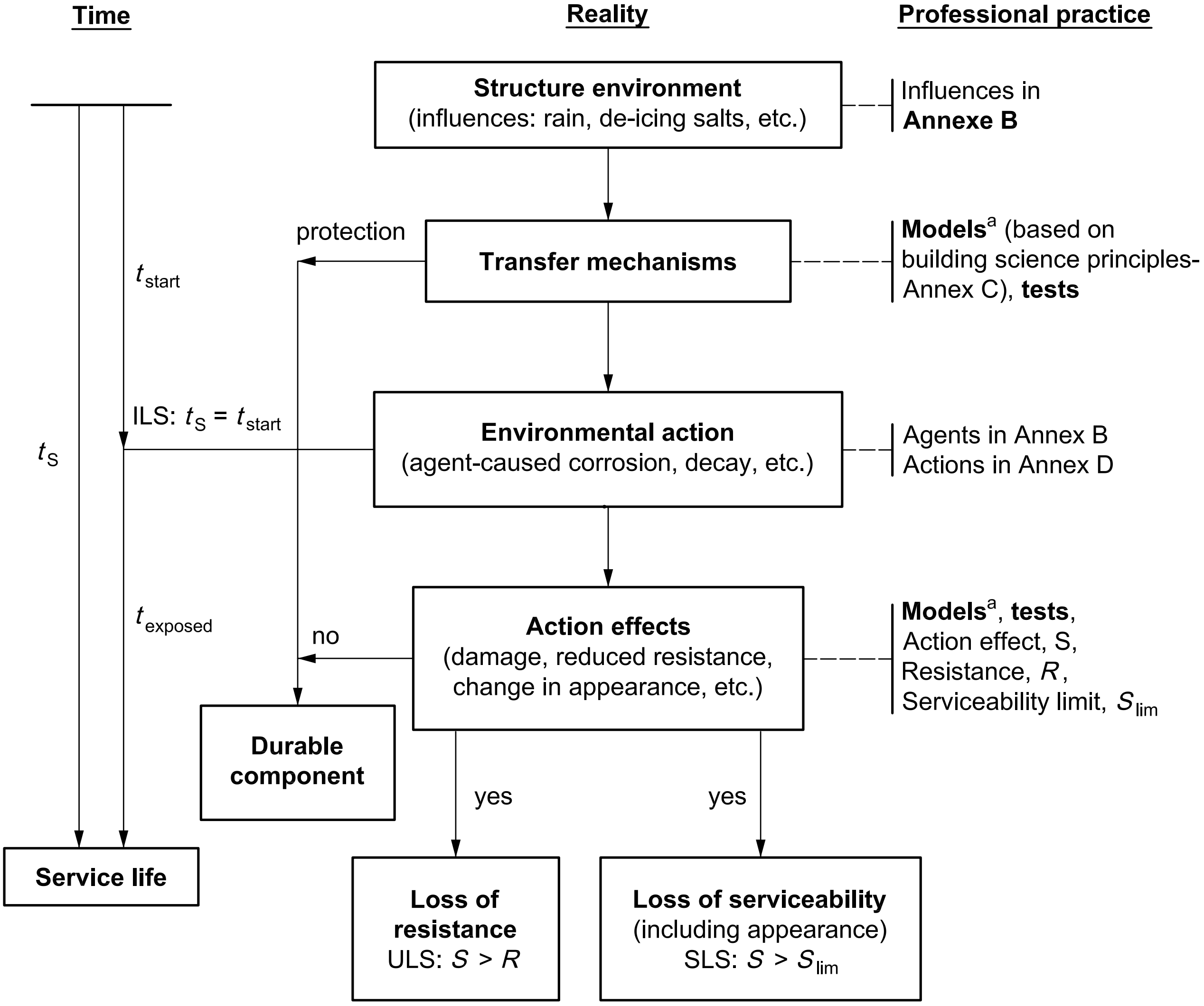
NOTE 3 Transfer mechanisms can also include a manufacturing process that results in a self-ageing degradation without agents transferred from the structure environment, for example the addition of sea sand into the concrete mix.

6.4 Environmental action

An environmental action, such as corrosion, decay or shrinkage, is a chemical, electrochemical, biological (e.g. insect attack), physical (e.g. UV) or mechanical action causing material deterioration or deformation. Except for mechanical action, an environmental action is the consequence of the expected environmental agents, such as moisture, oxygen and temperature, the chemical, electrochemical and physical properties of the materials of the components, and the interaction of the different components, including electrochemical (e.g. galvanic corrosion) and physical (e.g. deformation) interactions. Environmental actions, such as corrosion of steel, decay of wood, shrinkage or freeze-thaw of cement-based materials such as masonry or concrete, can result in loss of performance.

For examples of agents affecting different materials, see Annex B.

For examples of environmental actions, see Annex D.



[a] Both conceptual and mathematical.

Figure 1 — Limit-states method for durability

6.5 Action effects

Action effects include damage, loss of resistance, internal force/stress or unacceptable appearance due to material deterioration, or displacement due to material deformation. An action effect can result in the loss of performance as defined by one or more of the limit states given in 6.6.

For examples of action effects, see Annex D.

6.6 Limit states

6.6.1 Ultimate limit state

For material deterioration resulting in failure due to loss of resistance, the ultimate limit state is defined when the resistance of the component or structure becomes equal to, or less than, the internal mechanical force. See Clauses A.1 and A.2.

6.6.2 Serviceability limit states

For material degradation, the serviceability limit states are defined by

- local damage (including cracking) or change in appearance that affects the function or appearance of structural or non-structural components,
- relative displacements that affect the function or appearance of structural or non-structural components.

6.6.3 Initiation limit state

This limit state is defined by the initiation of deterioration of a component that precedes the occurrence of the serviceability or ultimate limit states. The time to reach this limit state is designated by t_{start} in Figure 1. See Clause A.3.

NOTE 1 A deterioration or deformation occurring on or inside a structure does not necessarily mean failure. Therefore, it is important to consider not only the environmental action and action effects, but also the limit states (e.g. fracture, movements, gaps, appearance, material weakening) that correspond to functional failure of the component for its intended use. Examples are given in Annex D of the forms of failure associated with prevalent environmental actions for materials.

NOTE 2 Although not within the scope of this International Standard, mould growth due to moisture accumulation on components can also serve as a limit state affecting human health.

7 Durability requirements

7.1 Basic durability requirement

Structures and their components shall be conceived, designed, constructed and operated, inspected, maintained and repaired in such a way that, under foreseeable environmental conditions, they maintain their required performance during their design lives with sufficient reliability for the safety and comfort of users and the intended use of the structure.

The service life, t_{S}, of the structure and its components shall meet or exceed the design life, t_{D}, as expressed in Equation (1):

$$t_{\mathrm{S}} \geqslant t_{\mathrm{D}} \tag{1}$$

When a component is protected against agents (e.g. concrete cover of reinforcement, zinc coating of steel, preservative treatment of wood), the service life, t_{S}, can be determined as given in Equation (2) (see Figure 1):

$$t_{\mathrm{S}} = t_{\mathrm{start}} + t_{\mathrm{exposed}} \tag{2}$$

where

t_{start} is the time of the initiation of deterioration;

t_{exposed} is the service life after initiation of the deterioration.

The service life of the structure is based on the service lives of all the components, management procedures, inspection, maintenance, repair and replacement strategies for the structure and its components to ensure functionality over the design life of the structure.

Components whose predicted service life is less than the design life of the structure shall be inspectable and replaceable.

In the event of renovation, the design life of the revised structure shall be reconsidered.

In the event of repairs necessary to correct damage or premature deterioration, the repairs shall be designed, constructed and maintained to provide the required performance over the design life agreed upon between the owner and the designer.

7.2 Formats for checking durability

7.2.1 General

The basic durability requirement formulated in 7.1 shall be checked in one of the following two ways:

- by the service-life format in 7.2.2;
- by the limit-states format in 7.2.3.

7.2.2 Service-life format

The service-life format consists in specifying the design life, t_D, of the component or structure in accordance with Clause 8, and in determining the predicted service life, t_{SP}, of the component or structure in accordance with Clause 9 for a target reliability selected in accordance with 8.6.

For service-life prediction based on data from experience and tests (e.g. the factor method in 9.3.2.4), the basic requirement of 7.1 is given by Equation (1) with $t_S = t_{SP}$.

For a service-life prediction based on the limit-states method using the probabilistic format in 9.3.2.2, the basic requirement of 7.1 is as given in Equation (3):

$$P(t_S \leqslant t_D) \leqslant P_{target} \tag{3}$$

where the service life, t_S, is modelled mathematically as a function of basic variables X_i, Y_i and time t, where X_i is a function of agent transfer for t_{start} in Equation (2), and Y_i is a function of damage or resistance for $t_{exposed}$ in Equation (2). See Figure 2 and Clause A.3.

Alternatively, this limit state can also be checked using a partial factor format (see also 9.3.2.3):

$$t_{Sk}/\gamma_S \geqslant t_D \text{ and } \gamma_S \geqslant 1{,}0 \tag{4}$$

where

t_{Sk} is the characteristic value of t_S as defined in 3.5;

γ_S is a partial factor calibrated in accordance with ISO 2394 to satisfy Equation (3).

7.2.3 Limit-states format

7.2.3.1 Ultimate limit state

The basic requirement for the ultimate limit state (ULS) defined in 6.6.1 at any time, t, during the design life of the component, t_D, is given by Equation (5):

$$R(t) \geqslant S(t) \tag{5}$$

where

$R(t)$ is the resistance capacity of the structural component at time t;

$S(t)$ represents the action effect (e.g. an internal force or stress) at any time t.

$R(t)$ and $S(t)$ are modelled mathematically as a function of the basic variables, X_i, Y_i and t, in accordance with ISO 2394. The ULS condition given in Equation (5) is ensured by checking that, at any time t, the conditions in Equation (6) hold:

$$P_f(t) = P[R(t) - S(t) < 0] < P_{\text{target,ULS}} \tag{6}$$

$R(t)$ and $S(t)$ are depicted in Figure 2. The probability of failure, P_f, is indicated in Figure 2 as the region below the horizontal axis for time t. This probability should not exceed $P_{\text{target,ULS}}$, as determined in accordance with 8.6 (see Figure 2).

7.2.3.2 Serviceability limit states

The basic requirement for the serviceability limit states (SLS) defined in 6.6.2 at any time, t, during the design life of the component, t_D, is given by Equation (7):

$$S_{\text{lim}} > S(t) \tag{7}$$

where

$S(t)$ is the action effect (e.g. a stress or deformation) at any time t;

S_{lim} is the serviceability limit (see Figure A.6).

$S(t)$ is modelled mathematically as a function of basic variables, X_i, Y_i and t, causing damage or loss of appearance. The SLS condition in Equation (7) is ensured by checking that the conditions in Equation (8) hold:

$$P_f(t) = P[S_{\text{lim}} - S(t) < 0] < P_{\text{target,SLS}} \tag{8}$$

In practice the limit state conditions in Equations (5) and (7) can also be checked using a properly calibrated, partial factor design check format as described in ISO 2394. Equations (6) and (8) serve as the basis for calibrating partial factor design check equations associated with Equations (5) and (7).

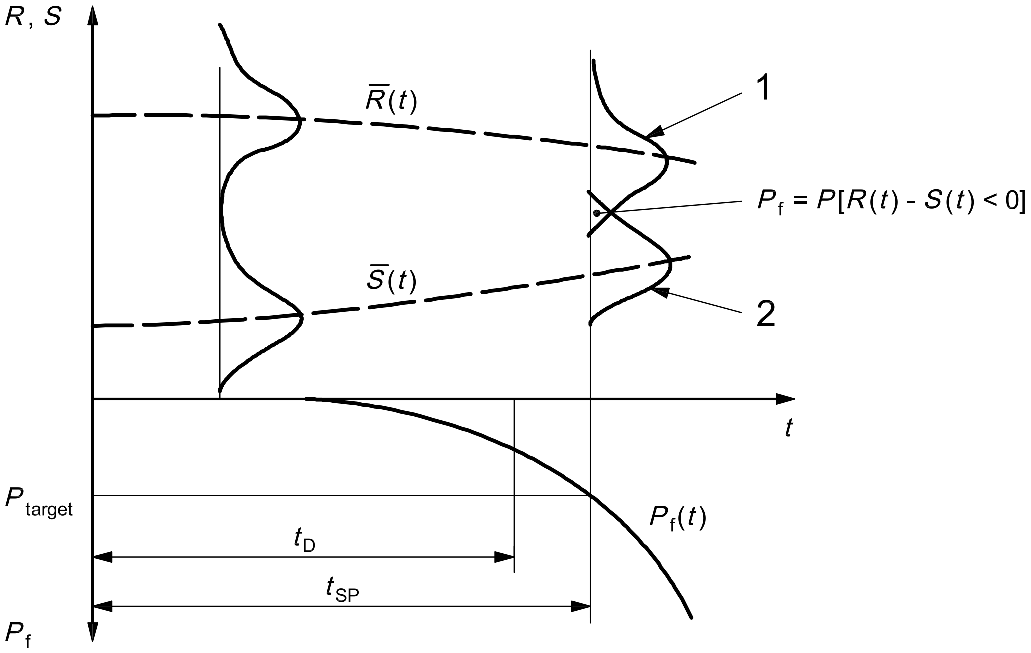
NOTE Figure 2 shows the service life, t_S, as a random variable having its own cumulative probability function as indicated below the horizontal axis in Figure 2. The service life can be found as the time at which R no longer exceeds S for the ULS, or S_{lim} no longer exceeds S for the SLS. In the case of cumulative probability functions as shown in Figure 2, there is a one-to-one correspondence between the basic durability requirement embodied in the service-life format, Equation (3), and the limit state format, Equations (6) and (8). This applies to material deterioration and to material deformation that is cumulative. For cyclic material deformation due, for example, to annual cyclic moisture or temperature changes, the limit-states format in ISO 2394 is recommended. The effect of interventions, such as protective treatment of wood during the service life, is indicated in Figure 3 (see also Clause A.2 for a case regarding a timber power pole).

7.2.3.3 Initiation limit state

The basic requirement for the initiation limit state can be evaluated in accordance with 7.2.3.1 or 7.2.3.2 by assuming that $t_{\text{exposure}}(Y_i,t) = 0$. See Clause A.3.

7.2.4 System durability versus component durability

The limit state analysis for durability using Equations (1), (2), (5) or (7), is equally applicable to structural systems as to the individual components of a structural system. If a system can be described in terms of a well-defined, logical assembly of components, then systems analysis, such as fault-tree or cause-tree analysis, can be applied to determine the durability of the system.

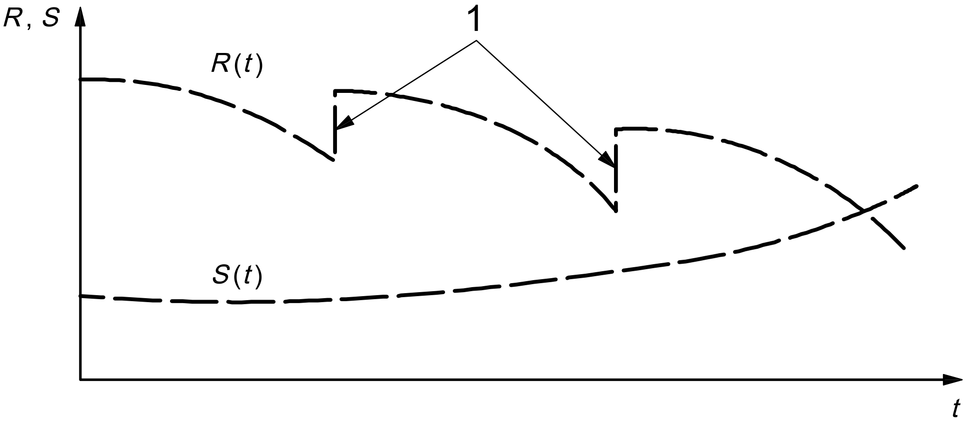


Key

1 probability density function of $R(t)$

2 probability density function of $S(t)$

Figure 2 — Mathematical model for predicting service life



Key

1 interventions

Figure 3 — Model for predicting service life, taking into account interventions

8 Design life of a structure and its components, t_D

8.1 Structure

The design life of a structure should be agreed with the client and the appropriate authority. Typical design life categories for structures are given in ISO 2394:1998, Table 1.

8.2 Components

The design life of a component should be determined considering

- the design life of the structure,
- exposure conditions (environmental action),
- difficulty and cost of maintenance or replacement, taking into account its accessibility,
- the consequences of failure of the component in terms of costs of repair, disruption and operation, and the hazard to users or others (see Table 1),
- current and future availability of suitable components,
- technical or functional obsolescence.

8.3 Component service life related to the design life of the structure

Permanent components (foundations and main structural members) should be expected to perform for the design life of the structure with a high reliability (low probability of failure). Components whose design life is less than that of the structure (or an assembly of components of a structure) should be designed to be accessible to allow inspection, repair or replacement, as well as the maintenance requirements. A rational, long-term plan for maintenance of the structure and its components, including planned repair and replacement, should be set up as recommended in Clause 10.

8.4 Difficulty and cost of maintenance or replacement

Individual components can be classified into categories of maintenance (for example “little or none”, “significant” or “extensive”) by considering costs, extent and frequency of disruption for users (e.g. access). The selection or design of components and the specification of the necessary maintenance should be determined by life-cycle cost (including user cost) for economy or life-cycle assessment for sustainability. To extend the service life, inherent superior durability or implementation of a more comprehensive maintenance programme, or both, should be specified.

NOTE 1 Methods of life-cycle cost (for economy) are provided in ISO 15686-5.

NOTE 2 Methods of life-cycle assessment (for sustainability) are provided in ISO 15686-6.

8.5 Consequences of failure

Table 1 identifies four categories of failure. Components whose failure threatens life or health or causes major disruption should be designed to provide a greater reliability during the design life than those whose failure does not threaten life or health or cause major disruption.

8.6 Selection of target reliability

Reliability of the durability of the structure and of each component shall be chosen based on the design life of the structure, the component design life related to the design life of the structure and the difficulty and expense of maintenance and consequences of failure, as given in 8.2 to 8.5. The serviceability criteria and the appropriate level of reliability should be agreed with the client and the appropriate authority.

NOTE Recommended target reliabilities (expressed in terms of the reliability index, β) are provided in ISO 2394:1998, Table E.2.

Table 1 — Categories of component failure

Category	Consequences of failure	Examples
1	Minor and repairable damage, no injuries to people	Components where replacement after failure is planned for, or where other reasons for replacement are more relevant, like coatings or sealants
2	Minor injuries or little disruption of the use and occupancy of the structure, including components that protect other components essential for the function of the assembly	Replaceable but important components for the function of the structure, such as installations for heating, lighting and ventilation or windows, whose replacement is planned before failure
3	Non-serious injuries or moderate economic, social or environmental consequences	Non-heavy, non-structural components of the facility requiring major repair work if they fail, such as plumbing, or components/systems whose replacement is planned before failure, such as structural bearings and railings or cladding
4	Loss of human life or serious injuries, or considerable economic, social or environmental consequences	Structural components that are parts of the primary or secondary load-carrying system, emergency exits or components causing major damage if they fail (e.g. heavy parts of the envelope, prefabricated wall elements, heavy inner walls, etc.)

9 Predicted service life, t_{SP}

9.1 General

9.1.1 The predicted service life of the components or the structure as a whole shall be assessed taking into account

a) experience in accordance with 9.2,

b) modelling in accordance with 9.3,

c) testing in accordance with 9.4.

All methods used to determine predicted service life should be based on a sound understanding of building science principles in accordance with Figure 1.

9.1.2 For the prediction of service life of any component of the structure,

a) experience may be applied where identical assemblies have been used successfully and in the same environments,

b) modelling and experience should be applied where

- a similar component or assembly has been used successfully in the same environments, or
- proven components or assemblies have been used successfully, but in moderately different environments,

c) modelling and testing should be applied where

- innovative components and assemblies are going to be used, or
- proven components or assemblies are going to be used in significantly different environments.

9.1.3 The degree to which an assembly or its components are innovative, or the service life is dissimilar to the one previously experienced, should be established by the application of building science principles as described in Figure 1.

NOTE 1 The predicted service life of any component of the structure is approximate, based on the environmental action, damage, loss of resistance or unacceptable appearance assumed in the design, and on construction and maintenance procedures.

NOTE 2 Service-life prediction of products used in buildings and construction works based on experience and testing are provided in ISO 15686 (all parts). Service-life prediction of structures based on modelling durability, using conceptual or mathematical models in addition to experience and testing, are provided in this International Standard.

NOTE 3 Prescriptive requirements for durability of specific components are contained in current codes and standards and other sources. These requirements usually imply service lives of components which are consistent with current expectations and which may be considered appropriate for structures of medium or long design life.

9.2 Prediction based on experience

Procedures on the collection and use of data based on experience, by means of inspection of facilities, are contained in ISO 15686-2 [16].

Properly documented local experience, because it is based on reality, provides the most reliable information for traditional proven components and assemblies. Also, properly documented new experience of unexpected failures that occur as a result of innovation without adequate research is especially important to control future failures. Table D.1, for example, is based on experience as well as research. For innovative components and assemblies, or where non-traditional components and assemblies known to be effective in one environment are used in a significantly different environment, experience cannot be relied upon; testing and modelling (research) are also necessary.

9.3 Prediction based on modelling

9.3.1 Conceptual modelling

Conceptual modelling in the design for durability is the application of building science principles in accordance with Figure 1 and Annexes B, C and D. This applies to the structure environment, transfer mechanisms, environmental action, and action effects leading to failure. An example of application of conceptual modelling in accordance with building science principles (Figure 1) for the design for durability is provided in Clause A.1.

9.3.2 Mathematical modelling

9.3.2.1 General

Specific models are material-dependent and, therefore, belong to material design standards.

9.3.2.2 Probabilistic format

Following the selection of target failure probabilities in accordance with the consequences of component failure (see 8.5) for the limit states in 6.6, a structural-reliability analysis can be performed to check if either Equations (2) and (3) or Equations (6) or (8) are satisfied. Guidance is given in ISO 2394. See Clauses A.2 and A.3.

9.3.2.3 Partial factor format

Durability can be verified by checking if specific design check equations are satisfied. Equation (4) can be used to check if the factored characteristic service life exceeds the design life. The factor γ_S in Equation (4) is calibrated in such a way that Equation (3) is satisfied. Guidance about partial factors and calibration can be found in ISO 2394.

9.3.2.4 Factor method

An empirical calculation method for estimating service life is described in ISO 15686-8. The factor method is based on the reference service life obtained through experience and testing under specified conditions. Seven factors (component quality, design details, site work, indoor environment, outdoor environment, use conditions and maintenance) are chosen for the particular application and location, multiplied together to give γ_S in Equation (4), and applied to a reference service life, t_{ref}, to estimate a characteristic service life, t_{Sk}. The predicted service life, t_{SP}, can then be estimated by Equation (4) (see 7.2.2).

NOTE See ISO 15686-8 [19] for alternative formats for the factor method and for the application of the factor method.

9.4 Prediction based on testing

Testing of components or assemblies is carried out to estimate the predicted service life, $t_{SP,}$ caused by mechanisms that occur at the various stages as depicted in Figure 1, including transfer mechanisms resulting in environmental actions leading to damage and loss of resistance, or unacceptable appearance.

Procedures on the application of testing, including accelerated testing*,* for estimating the predicted service life are contained in ISO 15686-2 [16].

10 Strategies for durability design

The design process for service-life planning is described in ISO 15686-1 [15]. One part of that process is to design for durability. When the design service life is known, materials, components and design, including detailing and other reliable measures to lengthen the life, should be chosen so that the predicted service life, with a target probability of failure, exceeds the required design life. Service life prediction, especially by experience and testing, is covered in ISO 15686-2 [16]. Service life prediction by design principles for modelling durability are described in this International Standard. However, ISO 15686-1 [15] still provides the framework for the design procedures for service-life planning.

Durability also depends on the quality of the construction as well as construction details, such as those details that ensure continuity of heat, air and moisture protection within an assembly such as the building envelope. To ensure quality during construction, design documents should identify all the critical details and quality of materials for inspection and commissioning reviews during the construction process, independent of who is performing the construction quality control, the designer or inspector. Critical details that are important to check include, for example, thickness of coating, and depth of concrete cover.

To achieve the design life of a structure or a repair, all details and components shall be designed for that service life, with or without planned maintenance and repair; otherwise a replacement shall be planned and prepared for. It is strongly recommended to prepare a maintenance/repair/replacement plan for the structure at the design stage. In the maintenance plan, all the assumptions made in the design phase shall be considered, for example the need for preventive maintenance, such as inspection and cleaning, to reduce cumulative damage, inspection, maintenance and repair of the structure along with the protective and sheltering measures, and finally replacement.

Annex E provides an example of procedures for ensuring durability throughout the design service life of the structure, including feedback of premature failures for future practice. The actual procedures, however, depend on local practice and the type of facility.

NOTE 1 There are a variety of measures that can be used to increase the service life, including selection of materials, providing barriers (e.g. zinc, special paints, anodic protection, preservative treatment of wood), detailing to minimize time of wetness (see Annex C) where exposure to environmental action is unavoidable (see Table D.1).

NOTE 2 Procedures for considering impacts on the environment (for sustainability) in the design of structures for durability are contained in ISO 15686-6.

Annex A
(informative)

Examples of the application of the limit-states method

The following examples illustrate the application of the limit-states method in Figures 1 and 2 for the prediction of service life using mathematical as well as conceptual models. These examples are provided for illustrative purposes only. The models are material-dependent and, therefore, will be developed by other ISO/TCs.

A.1 Example A.1 — Application of the limit-states method for the design of a wood post for durability against fungal decay

A.1.1 General

In this example, conceptual models are used in the limit-states method of Figure 1 to design a structural component for durability. This example concerns the design and detailing of an exposed wooden post shown in Figure A.1 against failure caused by wood fungal decay (environmental action in Table D.1). In many similar structures, there is a roof over the assembly that fully or partially protects the post from exposure to moisture. Wood fungal decay is caused by specific types of fungi that metabolize the wood components, breaking down the wood structure. The spores of wood decay fungi are present in the air but require favourable moisture and temperature conditions for metabolism.

A.1.2 Structure environment

NOTE See Annex B.

For the outdoor atmosphere where the post is located, the structure environment contains fungal spores, rain, temperature, humidity and moisture from the ground. Decay hazard is generally defined by the combination of atmospheric temperature and moisture conditions and is location-specific. Decay-hazard maps have been published for some countries (see CSA 478-95, Figure C.4 [3]). In other locations, the decay hazard is determined by local knowledge.

A.1.3 Transfer mechanisms

NOTE See Annex D.

The transfer mechanisms listed in Table A.1, acting on the post over time, can cause influences on the structure environment to become environmental action in the wood post.

A.1.4 Environmental action

Combined together, spores, moisture and temperature are the agents causing decay of the untreated wood post. The untreated wood post begins to decay when the sustained wood moisture content is above 20 % (unit mass of moisture to wood) and the temperature is above freezing. Optimum conditions for decay occur when wood moisture content is between 30 % and 90 % and temperatures are between 20 °C and 35 °C.

Table A.1 — Transfer mechanisms acting on the post

Transfer mechanism that promotes environmental action	Transfer mechanism and detailing to minimize environmental action
Sustained exposure to moisture: Long-term exposure to rain Water trapped in joints and around connections	Prevention of moisture build-up: Cover the top of the post with railings or flashing. Detail to avoid water traps. Barriers to fungal deterioration: Where appropriate, use naturally decay-resistant species of wood. If required, use pressure-treated wood. The species of wood, type and level of treatment depend on the decay hazard and design life. Apply field applications of preservative treatments at all cuts, notches and connections.
Prevention of drying: Continuous high humidity Lack of ventilation	Optimization of ventilation: Design with spaces between framing members. Clear vegetation beneath the deck and around the post to allow ventilation.
Exposure to groundwater	Barrier: Use raised footings.

A.1.5 Loss of resistance

NOTE See Annexes B and D.

Decayed wood is not generally considered to provide structural resistance. Therefore, wood decay reduces the effective section properties of the wood member. The cumulative effect of degradation over time is to reduce the effective cross-section of the wood post and weaken the connections that are in the decayed portion of the post.

The wood post resists overturning forces from the railings and axial forces due to gravity actions on the deck. Where there is decay, the cumulative degradation of the post reduces the effective cross-section of the wood post and weakens the connection. Throughout the service life of the structure, it is the residual section of the wood post that is required to resist the overturning and axial loads. Connections are required to maintain enough residual capacity to support the deck. (See Figure A.1.)

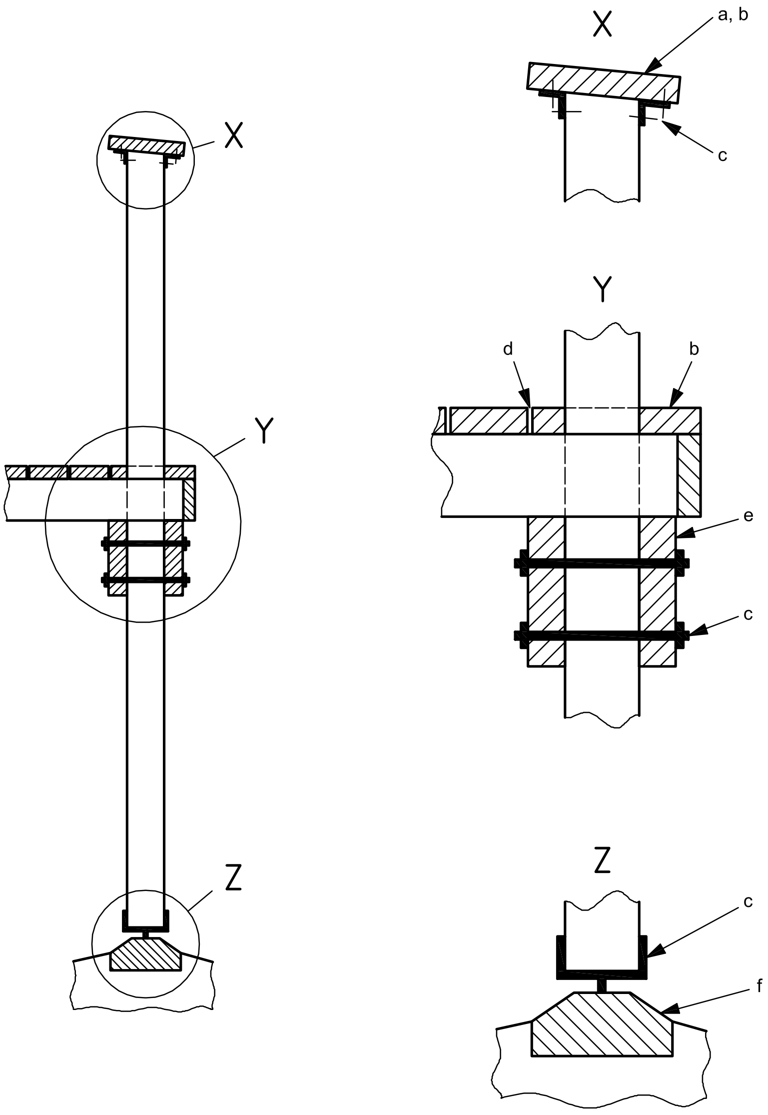
A.1.6 Inspection and maintenance

Wood posts are generally visible and easy to inspect. Decay can initiate at locations where wood seasoning checks extend beyond the wood treatment layer. Decay can also initiate where water accumulates, such as at the base of the post and at the connections. Regular application of wood stains or field-applied preservatives are used to extend the service life of wood decks.

A.2 Example A.2 — Service life of a timber power pole

A.2.1 General

During the past eight years, there has been a major national undertaking to develop procedures for engineering the durability of timber construction in Australia [8], [9]. This work is being used to develop a draft Australian timber engineering design standard. For this project, consideration was given to attack by decay fungi, termites, marine borers and corrosion agents. The structure environments considered included in ground, in sea water, exposed outdoors, and within a building envelope. Table A.2 provides an overview of the scenarios modelled.



[a] Cover the end grain at the top of the post. For enhanced drainage, angle the railing.

[b] Place railing and deck boards bark side up to reduce water accumulation.

[c] Use connections that minimize accumulation of water. If preservatives are used, apply a field application of the preservative at connections, cuts and notches and use corrosion-resistant fasteners compatible with the wood preservative treatment.

[d] Where possible, provide spaces between framing members to allow ventilation and drainage.

[e] Caulk tight joints to prevent moisture accumulation.

[f] Use raised footing. Slope footing to enhance drainage. Clear vegetation around the footing to allow ventilation.

Figure A.1 — Wood post supporting railing and wood deck — Detailing to extend service life

Table A.2 — List of scenarios modelled

Attack mechanism	Environment
Decay fungi	In-ground Exposed Building envelope
Termites	Building envelope
Marine borers	Coastal waters
Corrosion	Exposed Building envelope

The sources of data for this modelling include

- fundamental building science, and laboratory studies,
- field tests of small clear specimens,
- field tests of full-size structural members,
- in-service structures,
- expert opinion.

The primary source of data is from field tests on approximately 25 000 samples, including small, clear samples and full-size members. As far as possible, the locations of the field data sources were chosen so as to cover the climate range of Australia.

A.2.2 Basic model for degradation of timber structures

For each potential failure mode, an attack scenario of progressive decay from an exposed surface is postulated and a method of modelling based on Figure 1 developed for predicting the degradation of strength with time. This degradation, denoted by the parameter $k_0(t)$, is defined by Equation (A.1):

$$k_0(t) = \bar{R}_t / \bar{R}_0 \tag{A.1}$$

where

$\bar{R}_0$ is the mean value of the initial strength;

$\bar{R}_t$ is the mean value of the strength at time t.

In addition to the mean value, it is also necessary to make an estimate of the uncertainty of $\bar{R}_t$. This is denoted by the coefficient of variation, $V_{R,t}$, and includes an allowance for the uncertainties in modelling the degradation of strength.

The predictions of degradation are based on assumptions related to the attack mechanism (environmental action in Figure 1). The parameters that affect this include the following:

- environmental influences, such as climate, sea-water salinity and air pollution;
- material parameters;
- geometry, including the choice of decay pattern;
- parameters related to maintenance strategies.

A.2.3 Model of a power pole attacked by decay fungi

To illustrate the procedure used, this example is governed by the loss of bending strength (ULS) of a power pole embedded in the ground and attacked by decay fungi at the ground-line. In this case, the transfer mechanism in Figure 1 is direct exposure to environmental influences (see Table C.1). For this example, the timber power pole is considered to be untreated, de-sapped and decayed around the circumference only.

The circumferential decay is illustrated schematically in Figure A.2. Based on recent research [10], the decay penetration, d_t, into the timber at the ground-line is defined by an initial lag, t_{lag} (similar to t_{start} in Figure 1), and a decay rate, r, as illustrated in Figure A.3. All parameters used in the model have been obtained by an empirical fit to field data.

The decay rate, r, expressed in millimetres per year, is expressed as given in Equation (A.2):

$$r = k_{\text{wood}} k_{\text{climate}} \tag{A.2}$$

where k_{wood} depends on the timber durability class and k_{climate} depends on climate. The climate factor used is a complex function of the following climatic parameters: mean annual temperature, mean annual rainfall and the number of months per year in which the rainfall is less than 5 mm. The 5 mm monthly rainfall has been chosen as this turns out to be the minimum rainfall required to maintain decay on the surface of timber embedded in soil. Table A.3 gives values of k_{wood} for timber specified in terms of their in-ground durability classification in accordance with AS 5604. Table A.4 gives the values of k_{climate} computed for the zones shown in the hazard map in Figure A.4.

The effect of conventional maintenance treatments is to produce a lag or delay phase in the progress of decay as illustrated by the graph in Figure A.3. For example, the application of an external bandage impregnated with a diffusing chemical has been shown to delay circumferential decay by a period of approximately five years. Other maintenance treatments can prove to be more effective, and their effect can be incorporated into the model.

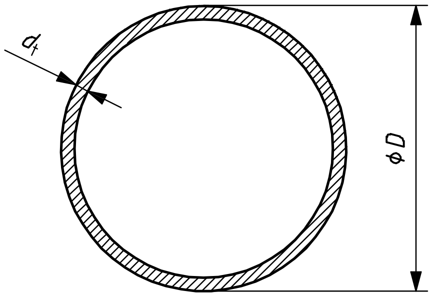
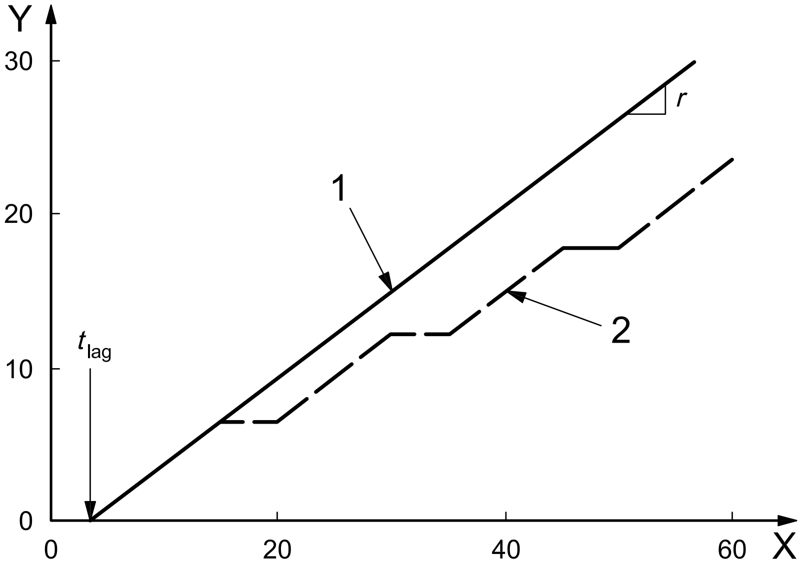


Figure A.2 — Schematic illustration of circumferential decay



Key

X time, t, expressed in years

Y decay penetration, d_t, expressed in millimetres

1 no maintenance

2 maintenance undertaken at 15 years, 30 years and 45 years

Figure A.3 — Progress of the mean depth of attack by decay

Table A.3 — Values of k_{wood} for outer heartwood

Durability class [a]	Degradation factor k_{wood}	Uncertainty of the degradation factor V_{wood}
1	0,165	0,45
2	0,38	0,55
3	0,65	0,75
4	1,40	0,90

[a] Durability class is as defined in accordance with AS 5604.

Table A.4 — Values of k_{climate} for outer heartwood

Zone [a]	Degradation factor k_{climate}	Uncertainty of the degradation factor V_{climate}
A	0,5	0,55
B	1,5	0,55
C	2,5	0,55
D	3,0	0,55

[a] Zone definitions are shown in Figure A.4.

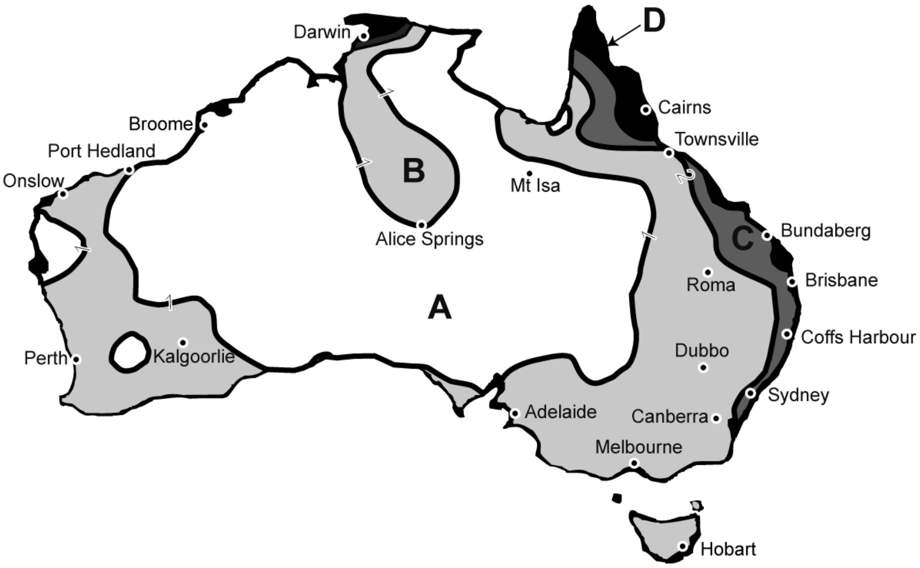


Figure A.4 — In-ground decay hazard map of Australia (Zone D is most hazardous)

The initial time lag, t_{lag}, expressed in years (analogous to t_{start} in Figure 1), is based on an empirical fit to the data, which is a function of the decay rate, r, as given by Equation (A.3):

$$t_{\text{lag}} = 3r^{-0,4} \tag{A.3}$$

For this example, it is assumed that the pole diameter, D, is equal to 300 mm, the timber is of durability class 2 and the pole is located in Zone B (see Figure A.4). From Tables A.3 and A.4, $k_{\text{wood}} = 0,38$ and $k_{\text{climate}} = 1,5$, resulting in a mean decay rate, r, equal to 0,57 mm/yr (Equation A.2) and a mean initial time lag, t_{lag}, of 3,76 years (Equation A.3). These values of r and t_{lag} define the mean decay depth, $\bar{d}_t$, plotted in Figure A.3.

The uncertainty of the decay depth, V_{d}, is determined from Equation (A.4):

$$V_{\text{d}} = \sqrt{V_{\text{wood}}^2 + V_{\text{climate}}^2 + V_{\text{model}}^2} \tag{A.4}$$

where

$V_{\text{wood}} = 0,55$ from Table A.3 for variations in k_{wood};

$V_{\text{climate}} = 0,55$ from Table A.4 for variations in k_{climate};

$V_{\text{model}} = 0,5$ for uncertainties involved in modelling the decay effects.

For a pole with diameter, D, the mean residual bending strength at time t, denoted by $\bar{R}_t$, is given by Equation (A.5):

$$\bar{R}_t = \frac{\pi}{32}\left(D - 2\bar{d}_t\right)^3 f_{\text{ult}} \tag{A.5}$$

where f_{ult} denotes the ultimate fibre strength of the undecayed wood. From Equation (A.5), the value of k_0 shown in Figure A.5 is given by Equation (A.6):

$$k_0 = \left(D - 2\bar{d}_t\right)^3 / D^3 \tag{A.6}$$

Using a first-order approximation [11], the coefficient of variation of the predicted loss in bending strength is given by Equation (A.7):

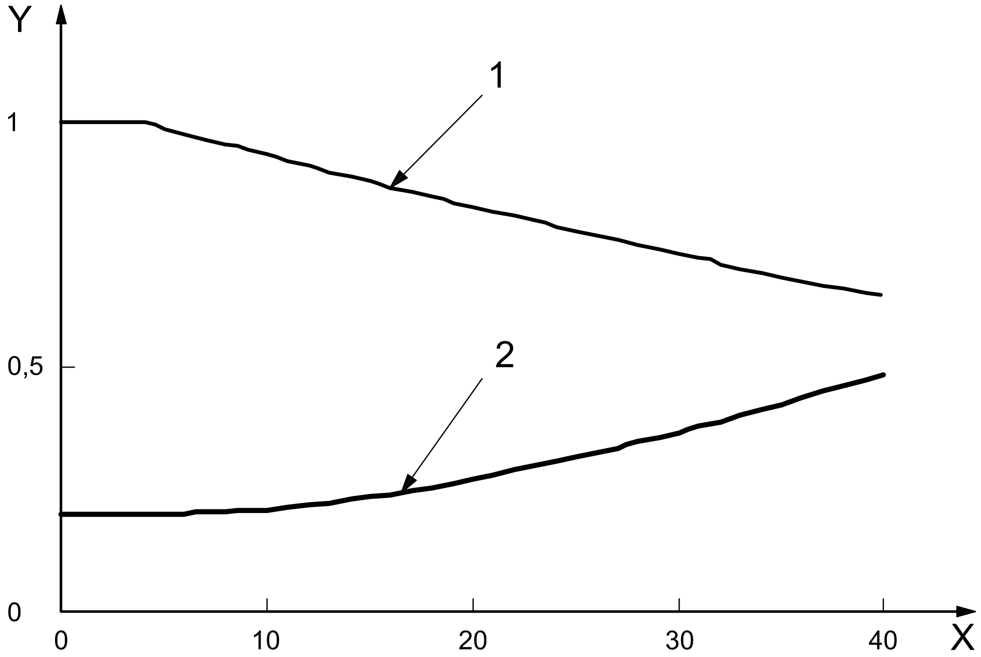
$$V_{\text{dur},t} = \frac{6V_{\text{d}}\bar{d}_t}{D - 2\bar{d}_t} \tag{A.7}$$

There are also uncertainties associated with the initial strength that it is necessary to consider. The initial COV of strength, $V_{R,0} = 0,2$, may be combined with $V_{\text{dur},t}$ to give an estimate of the uncertainty of the strength at time t, denoted by $V_{R,t}$, as follows:

$$V_{R,t}^2 = V_{R,0}^2 + V_{\text{dur},t}^2 \tag{A.8}$$

The values of $\bar{R}_t$ and $V_{R,t}$ for strength given in Equations (A.5) and (A.8) may be used, along with $\bar{S}$ and V_{S} for wind action, to compute the failure probability in accordance with Equation (6) for $P_{\text{f}}(t)$ as a function of time, as shown in Figure 2. Equations (A.6) and (A.8) evaluated for the 300 mm pole described earlier are shown in Figure A.5. These parameters can be used to compute the predicted Service-life, t_{SP}. The probability that this Service-life is greater than, or equal to, the specified design life, t_{D}, is given by the value specified for $P_{\text{target,ULS}}$.

The time for pole replacement may be specified as either (a) the specified design life, t_D, or (b) when inspection reveals that the depth of decay exceeds the value expected at the end of the design life as shown in Figure A.3.



Key

X age of the pole, t, expressed in years

Y strength degradation of the pole

1 $k_0(t) = \bar{R}_t / \bar{R}_0$

2 coefficient of variation, $V_{R,t}$

Figure A.5 — Effect of age of pole on the strength degradation, $k_0(t)$, and the coefficient of variation, $V_{R,t}$

A.3 Example A.3 — Service life of a concrete structure determined by carbonation-induced corrosion of reinforcement

A.3.1 General

In the following example, mathematical models based on the initiation limit state (initiation of significant corrosion of reinforcement; see 3.13, 6.6.3 and 7.2.3.3) are used to estimate the service life of reinforced concrete. The models used here describe the main deterioration process, taking into account local variations in concrete quality and the environment.

NOTE The models used in this example [12] are based on data from 44 buildings in south Japan, including measured carbonation depths and inspected degree of reinforcement corrosion. The models used are consistent with the approach given in Reference [13], prepared by International Federation for Structural Concrete, and considered together with this International Standard as the basis for further work on design for durability of concrete in ISO/TC 71.

A.3.2 Limit-states format

NOTE See 7.2.3.2.

Carbonation-induced corrosion of reinforcement is one of the typical examples related to the durability design of reinforced-concrete (RC) structures**.** The depth of the carbonated zone in concrete (characterized as an action effect, S, in 7.2.3.2) is assumed to proceed as following a function of square root of time as given by Equation (A.9):

$$S(t) = \alpha\beta\gamma t^{1/2} \tag{A.9}$$

where

$S(t)$ is the depth, expressed in millimetres, of the carbonated zone at a given time t, expressed in years;

α is a coefficient dependent on local environmental actions, such as the concentration of CO_2, atmospheric temperature and humidity;

β is a coefficient dependent on the finishing materials on the concrete surface;

γ is a coefficient dependent on the quality of concrete.

Because of the heterogeneity of concrete and the variability of local environmental actions and of workmanship, the carbonation depth varies randomly from point to point. Concrete cover depth (a basic variable characterized in 7.2.3.2 as a serviceability limit, S_{lim}), has a random distribution because of the construction variations. To account for the variations, the following assumptions are introduced.

a) The depth of carbonated zone is assumed to be normally distributed for the example, although other distributions can be used. The coefficient of variation is assumed to be constant.

b) The cover depth is also assumed to be normally distributed. To avoid occurrence of negative values, a lognormal, gamma or beta distribution is more realistic.

c) Reinforcement embedded in outdoor concrete is assumed to start to corrode when the carbonated zone reaches the surface of the reinforcement, such as for uncoated steel reinforcement.

Figure A.6 shows the relationship between carbonation and cover depth as a function of time.

For the normal distribution, the potential for corrosion initiation (i.e. the limit state function) is given by the difference between the cover depth and the depth of carbonated zone as given by Equation (A.10):

$$f\left[S_{\mathrm{lim}}-S(t)\right]=\frac{1}{\sqrt{2\pi\left[\bar{S}(t)^2V^2+\sigma^2\right]}}\,.\,\exp\left\{\frac{-\left\{\left[S_{\mathrm{lim}}-S(t)\right]-\left[\bar{S}_{\mathrm{lim}}-\bar{S}(t)\right]\right\}^2}{2\left[\bar{S}(t)^2V^2+\sigma^2\right]}\right\} \tag{A.10}$$

where

$\bar{S}(t)$ is the mean value of the depth of carbonation;

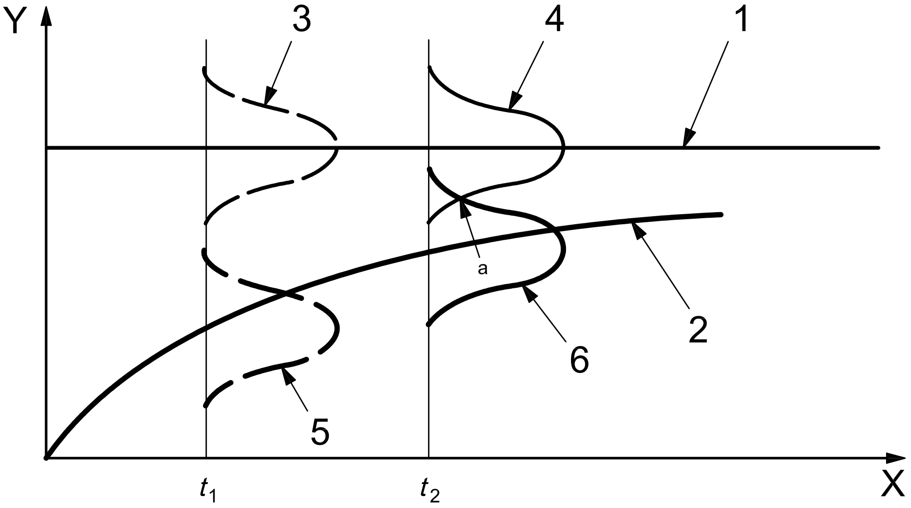
V is the coefficient of variation of the depth of carbonation;

$\bar{S}_{\mathrm{lim}}$ is the mean value of the cover depth;

σ is the standard deviation of the cover depth.

Consequently the probability of corrosion initiation at a given time, t, expressed in years, due to carbonation initiation is estimated based on Equation (8) as given by Equation (A.11):

$$P(t)=\int_{-\infty}^{0}f\left[S_{\mathrm{lim}}-S(t)\right]\cdot d\left[S_{\mathrm{lim}}-S(t)\right] \tag{A.11}$$



Key

X	time, t, expressed in years
Y	cover depth, S_{lim} (for curves 1, 3 and 4), or the depth of the carbonated zone, $\overline{S}(t)$ (for curves 2, 5 and 6)
1	curve of the cover depth, S_{lim}
2	curve of the depth of the carbonated zone, $\overline{S}(t)$
3	curve of the distribution of cover depths, S_{lim}, at time t_1
4	curve of the distribution of cover depths, S_{lim}, at time t_2
5	curve of the distribution of the depths of the carbonated zone, $S(t)$, at time t_1
6	curve of the distribution of the depths of the carbonated zone, $S(t)$, at time t_2

[a] The overlap of the distributions shown as curves 4 and 6 indicates the possibility of a failure.

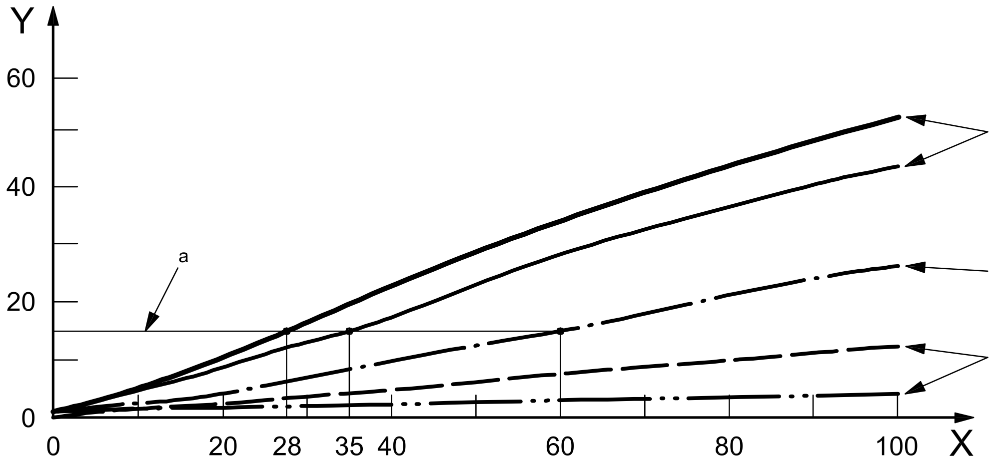
Figure A.6 — Relationship of carbonation and cover depth relative to failure

The design cover thickness for the maximum allowable probability of corrosion initiation can be determined once the standard deviations and coefficients in Equations (A.9) and (A.10) are known.

For example, the following values are assumed, based on available data for ordinary concrete:

- α = 1,0 (for outdoor concrete);
- β = 1,0 (no finishing of concrete surface);
- $\gamma = f(w/c)$, where w/c is the ratio of water to cement; see Reference [12];
- V = 0,4;
- σ = 15 mm.

The probability of corrosion initiation is calculated as a function of w/c for a given cover depth. Figure A.7 shows an example for a design cover depth of 40 mm. Assuming that the service life is terminated when the probability of corrosion initiation reaches 15 % (target probability for initiation limit state), the predicted service life of concrete structures is estimated as shown in Figure A.7.



Key

X time, t, expressed in years

Y probability of corrosion initiation, P, expressed in percent

1 high w/c

2 medium w/c

3 low w/c

[a] $P_{target} = 15\ \%$.

Figure A.7 — Relation between probability of corrosion and predicted service life [12]

A.3.3 Service-life format

This example can also be expressed using the service-life format in 7.2.2, Equations (3) and (4). It is recognized that the CO_2 penetration (a chemical process causing a decrease of pH providing the condition for reinforcement corrosion) is a transfer mechanism, modelled by Equation (A.9). To calculate t_{SP}, the limit state is conservatively defined as the corrosion initiation when the CO_2 reaches the reinforcement. This corresponds to t_{start} in Figure 1. By inverting Equation (A.9), the mathematical model for the agent transfer provides t_{SP}, as given by Equation (A.12):

$$t_{SP} = t_{start} = \left[\frac{\bar{S}_{lim} - 0{,}5\sigma}{(1+V)\alpha\,\beta\,\gamma}\right]^2 \qquad \text{(A.12)}$$

The service-life format provides the same solution for the limit state of corrosion initiation as the limit-states format.

NOTE It is possible to calculate the time after corrosion initiation for cracking/spalling of the concrete, $t_{exposed}(Y_i)$, where Y_i are the basic variables suitable for describing the cracking of concrete. It is expected that the basic variables include the build-up of corrosion products, diameter of the bar, bar spacing, cover and mechanical stress in the concrete [13], [14].

Annex B
(informative)

Examples of influences (structure environment) and agents (environmental action)

B.1 General

In designing for durability using the limit-states method (see Figure 1), the structure environment (the macro-environment) contains influences outside the structure (atmospheric and ground conditions, including pollution) and inside the structure (indoor atmosphere and materials), that are transformed into one or more agents on the surface of or within a component (the micro-environment) causing environmental action. Table B.1 lists the most common influences in the structure environment affecting the durability of structures and their components. Table B.2 lists the most common agents causing environmental actions that affect the durability of components.

This annex lists most of the influences and agents causing environmental actions that deteriorate and deform materials leading to damage and failure of components. Annex C provides information on the mechanisms that transfer environmental influences into agents on or within a component. Annex D provides a list of environmental actions and action effects that have caused failure in the past.

Table B.1 — Examples of influences (structure environment)

Location	Influence
Outside — Atmosphere	Rain, snow or ice Air constituents Air contaminants (e.g. salt spray) or pollutants Wind Temperature and humidity Sun
Outside — Ground or water	Water Soil constituents Soil spills/leaks Road salt
Inside	Humidity and temperature Contaminating materials (e.g. salty water from cars) Water (e.g. swimming pools or leakage) and sewage Stored chemicals Activities causing wear

Table B.2 — Examples of agents causing environmental action

Influences	Agents	Examples of parameters [a]
Moisture constituents	Solid (ice, snow) Liquid (rain, condensation) Gas (water vapour)	TOW, RH
Moisture contaminants	Chlorides, acids, sulfates	TOE, RH, pH, concentration
Air constituents	O_2, CO_2	TOE, concentration
Air contaminants	Oxides, particulates, sea spray	TOE, concentration
Ground constituents	Sulfates and other salts Acids (from decomposition of organics)	TOE, RH, pH, concentration
Ground contaminants	Chemicals from spills and leaks Chlorides from road salt Induced electric currents	TOE, RH, pH, T, concentration
Biological life	Microorganisms, insects, animals, plants	TOW, RH, T, geographical
Temperature	Freeze-thaw cycles	F-T(T, t)
Solar radiation	UV radiation, IR radiation	TOE, T, RH
Incompatible chemicals	—	TOE, concentration
Use or exposure	Wear, abrasion	TOE, load

[a] Expansion of abbreviations; see also B.3.2:

TOW	time of wetness	pH	acidity
TOE	time of exposure	t	time
F-T	freeze-thaw cycles	concentration	concentration of constituents and contaminants
T	temperature	load	mechanical load

B.2 Agents causing environmental action

B.2.1 General

Chemical action takes place continuously in many component materials. These actions may be beneficial (e.g. increase of concrete strength during and after curing) or detrimental (embrittlement of plastics exposed to UV radiation). Chemical actions depend on material constituents of a component and agents such as moisture, temperature and oxygen. Frequently, the environmental action due to one agent is dependent on the presence of another, for example moisture combined with oxygen.

Physical action, such as temperature and moisture fluctuation, can result in damage or separation of components that allow transfer of moisture or humid air, increasing the risk of failure due to material deterioration.

B.2.2 Moisture and contaminants

Water in the atmosphere in its various states (gas, liquid or solid) interacts with material surfaces in several forms: adsorbed moisture (low relative humidity); condensed water (high relative humidity, e.g. dew); and precipitation (e.g. fog, rain, snow). Water plays a major role in the corrosion of metals, the decay of wood and the deterioration of other materials, either as an active agent or as a means for transfer of other agents.

Most organic and many inorganic materials are porous and permit ingress of moisture to varying degrees. Porous materials with high moisture levels can be fractured by the expansive forces exerted when the contained water freezes. Fluctuations in the moisture content of porous materials can cause them to expand and contract as moisture is absorbed and given off. These deformations can result in damage to components and loss of performance. Organic materials, such as wood, also decay if exposed to excessive moisture in the presence of oxygen and fungi.

The formation and growth of ice lenses in moist, fine-grained soils can cause serious damage through frost heave of foundations or by lateral displacement of retaining walls. The source of water can be from rain, moisture migration from the ground or from the interior of a building, or melt water when frost or ice formed on a surface melts.

Chloride contaminants from de-icing salts are found in abundance and are a major cause of much deterioration in roadway infrastructure and parking garages in cold regions. They can also originate from industrial sources, such as hydrochloric-acid manufacturing plants and from the combustion of coal, paper and chlorine-containing plastics.

Acid rain (or snow or mist) is caused by the introduction of sulfur and nitrogen oxides into the air, primarily from the burning of coal, gasoline and oil, and from motor-vehicle traffic. This new climatic situation in the atmosphere produces a number of problems, including deterioration of structures (e.g. limestone buildings), in addition to affecting life itself.

B.2.3 Air and contaminants

Air, like water, is both an active agent and a means for transfer of other agents.

Atmospheric oxygen, when present with moisture, acts as an agent that causes corrosion and allows decay to develop in the presence of fungi. Carbon dioxide acts as an agent of corrosion of reinforcing steel by reducing the alkalinity of concrete (carbonation) and, as a consequence, the passivity against corrosion of concrete reinforcement.

Air provides a means for transfer of other agents, such as moisture and chlorides (sea spray). Air leakage through assemblies (e.g. the building envelope) is a major cause of problems, including condensation and rain penetration.

Particulate matter in the air deposited on surfaces can contribute to material deterioration, both physical and cosmetic. Hygroscopic deposits (e.g. salts, dusts, pollen) on material surfaces have been found to decrease the relative humidity at which a moisture film forms on a surface. The deposits depend on wind flow near the surface and the shape of the surface.

Chlorides in sea spray act as contaminants that contribute to atmospheric corrosion and stone deterioration in maritime regions. Since sodium chloride can take up water from the atmosphere at a low relative humidity, sea-salt deposits can pose severe durability hazards to metal cladding, especially on surfaces sheltered from rain.

B.2.4 Soils and ground contaminants

Any material placed in contact with soils and groundwater can be affected by the presence of contaminants. The effect of soil contaminants depends on their combination, concentration and type of soil. Contaminants such as solvents (e.g. gasoline) and oxidizing agents (e.g. acids) can react chemically and dissolve or degrade plastics. Bacterial activity can affect directly or indirectly the deterioration of materials in soils. Sulfate-reducing bacteria, found mostly on wet clay, boggy soils and marshes, are a typical example of bacteria affecting corrosion of metals.

Naturally occurring constituents of the soil promote deterioration, particularly in moist conditions. Salts dissolved in groundwater migrate in porous materials in contact with the ground and cause efflorescence, a common problem with masonry in contact with soil. Naturally occurring sulfates in some soils require the use of specially-formulated concrete and mortar mixes to avoid their destruction due to deterioration.

Stray electrical currents in the ground can accelerate corrosion of a metallic object at points where current leaves the object and enters the soil. This effect is pronounced in densely populated oil-production fields and within industrial complexes containing numerous buried pipelines.

B.2.5 Biological agents

Component materials can deteriorate from the direct action of living organisms (e.g. decay of wood by fungi) or from the action of by-products of plant or animal life (e.g. corrosion of metals by the action of sulfate-reducing bacteria).

Microorganisms are usually classified according to their ability to grow in the presence or absence of oxygen. Fungi that cause deterioration of timber need oxygen and moisture. A moisture content of less than about 20 % in timber is usually sufficient to prevent fungi from flourishing. Sulfate-reducing bacteria are most prevalent in environments depleted of oxygen.

The predominant insect problem is termite attack of wood and wood-based materials. Rodents such as mice and rats cause considerable damage by gnawing organic materials and PVC casings to electric cables. Birds and their nests and droppings can cause either mechanical damage (by pecking of soft materials) or chemical damage (corrosion of steel bridges exposed to bird droppings).

A major cause of damage from plants is the clogging of drains and gutters by roots and leaves, which leads to water damage of building components. Trees absorb water from the soil which, for some soils, can result in differential settlement.

B.2.6 Temperature

One of the most significant effects of temperature is the deformation of materials subject to variations in temperature. These deformations can result in damage to components and loss of performance. Roofing and cladding components are subjected to high temperatures in summer and cold temperatures in winter, and they should be allowed to expand and contract with temperature cycles. Thermal stresses cause buckling, bowing and sometimes breakage of components.

Although most chemical processes are accelerated by an increase in temperature, some are accelerated by a decrease in temperature. This occurs in the corrosion of metals, where low surface temperatures promote condensation on the surface, providing an environment favourable to corrosion. However, if the surface temperature is high, drying of the surface impedes corrosion.

B.2.7 Solar radiation

Organic materials such as polymers and wood can deteriorate if exposed to solar radiation. If radiation contains enough energy, however, it can cause a chemical reaction that results in a gradual change of the material properties, such as embrittlement, yellowing or fading of the colour. Sealants can either crack or lose adhesion at the interface.

Before solar radiation can affect a material, it is necessary for the radiation to be absorbed. The opacity, texture and colour of the surface, and its slope to the sun, considerably affect the ability of materials to absorb radiation. Also, the amount of high-energy UV reaching the ground decreases as the sun angle decreases.

UV radiation also interacts with other agents, such as temperature and moisture, to greatly increase deterioration.

The daily cycle of solar radiation can cause exposed surfaces to experience large temperature swings. This results in cyclic dimensional changes and can also increase the number of freeze-thaw cycles.

B.2.8 Chemical incompatability

Two materials in contact can cause or accelerate deterioration as a result of chemical interaction. Some examples are

- galvanic corrosion between dissimilar metal,
- accelerated corrosion of steel and zinc in certain woods and wood containing certain preservative chemicals,
- corrosion of lead and some aluminum alloys in contact with moist concrete or mortar,
- crazing or fracture of plastic in contact with certain sealants.

B.3 Examples of parameters for the structure environment and for environmental action

B.3.1 Structure environment

B.3.1.1 Acidity of precipitation

This is important for material deterioration, including corrosion. Normal rain is slightly acidic with a pH of approximately 5,6 (caused by CO_2 in the air). Organic acids and air pollution can further reduce the pH of rain to less than 5,0.

B.3.1.2 Driving rain index

The driving rain index (DRI), the product of the annual rainfall, expressed in metres, and the average wind speed, expressed in metres per second, is an indicator of the likelihood of rain wetting and penetrating external walls of buildings. It is usually classified into sheltered (DRI of 3 or less), moderate, and severe (DRI of 7 or more).

B.3.2 Environmental action

B.3.2.1 Time of wetness (TOW)

Time of wetness is one of the most important parameters for material deterioration. Corrosion, for example, takes place when a metal surface exposed to the atmosphere is covered by a film of water. The presence of such a film occurs when the relative humidity is above 80 % to 90 % and the temperature is above freezing. Also time of wetness depends on design details (e.g. retention of moisture between surfaces, gravity water traps; see Annex C). This parameter can be improved by the inclusion of other parameters such as temperature.

B.3.2.2 Time of exposure (TOE)

This is a generalization of time of wetness applied for a more specific agent causing environmental action, such as UV on plastic materials, or the concentration of chlorides in concrete adjacent to the reinforcement (see Figure 1). For examples, see Table B.2.

B.3.2.3 Freeze-thaw cycles (F-T)

This parameter is similar to the number of stress cycles causing fatigue damage to structural materials. The degradation mechanism, however, is different than for fatigue.

B.4 Severity classification for the structure environment

Once the degradation of a component has been assessed by experience, modelling or testing, the environmental influences (macro-environment) for the structure can be classified in terms of severity. The overall severity of the structure environment depends on a number of factors, including rainfall or driving rain index (DRI), temperature, humidity, rain pH, frost cycles, concentration of constituents and contaminants, decay hazard, indoor and ground conditions, as well as the materials stored inside. A number of material design standards have developed or are developing a classification of environmental severity suitable for the component materials. Such classifications are contained in References [1] to [7].

Annex C
(informative)

Examples of transfer mechanisms

C.1 General

Environmental action is caused by micro-environmental agents, acting alone or in combination, over time, resulting in deterioration or deformation of a given material. These agents generally occur as a result of influences in the structure environment outside or within the structure being transferred on, into or through an assembly of components. Table C.1 contains a list of these transfer mechanisms. Although little can be done to modify the structure environment (except indoors), the agents causing degradation can be controlled. Their control can be achieved from a fundamental understanding of the transfer mechanisms listed in Table C.1. The mechanisms of most concern are those that govern the flow of water, air, and heat.

In designing for durability, one can either select a material to resist degradation caused by the expected environmental action, or the environmental action must be altered to suit the material. Tables C.2 and C.3 provide simple examples of the application of an understanding of the transfer mechanisms in Table C.1 to the design of an assembly and its components.

Table C.1 — Examples of mechanisms that transfer influences in the structure environment into agents causing environmental action

Transfer mechanisms that usually promote environmental action	Transfer mechanisms that reduce environmental action
Direct exposure to environmental action	Barrier
Gravity	Drainage
Air and vapour pressure	Ventilation
Capillarity (surface tension)	Redundancy (e.g. combination of a barrier and drainage)
Kinetic energy (driving rain)	
Permeation	
Convection	
Condensation	
Diffusion	

Table C.2 — Examples of transfer mechanisms causing environmental action

Transfer mechanism	Examples
Direct exposure	UV on exterior surface materials Rain on roof or wall surfaces Ground moisture (plus contaminants) on foundation surfaces
Gravity	Water traps in lap joints, channels, column base, crevices Ponding on “flat” surfaces Rain penetration into building envelopes (especially roofs) Staining of building face by water runoff
Air/vapour pressure	Rain penetration into building envelopes (especially walls) Condensation in building envelopes due air leakage and vapour diffusion
Capillarity or surface tension	Penetration of rain and groundwater through porous materials (capillarity) or at joints (surface tension) Migration of salts within porous materials
Kinetic energy	Driving rain on wall surfaces and penetration through openings
Permeation	CO_2 ingress into concrete Vapour transmission through building envelope materials
Convection	Air leakage through gaps in building envelopes
Condensation	Onto surfaces whose temperature is below the dew point of adjacent air
Diffusion	Chloride ingress into concrete

Table C.3 — Examples of design and detailing to minimize environmental action

Transfer mechanism	Examples
Barrier	Coatings: zinc on steel, paint on wood Preservatives: treated wood Sealants (joints and surfaces) Damp-proofing and waterproofing (foundations) Membranes: concrete parking garages and bridge decks Air/vapour barrier system in building envelopes
Drainage	Detailing to avoid water traps Detailing to avoid rain penetration in building envelopes Drips to deflect moisture away from lower components De-watering systems
Ventilation	Detailing to promote escape of moist air in building envelopes
Redundancy (barrier + drainage/ventilation)	Rain-screen in building envelopes Two-stage joint in building envelopes Sheltering (roofing, cover) of highly-exposed parts (joints, wooden ends)

Annex D
(informative)

Environmental actions for structural materials and their control

D.1 General

This annex summarizes, in tabular form, examples of environmental actions and action effects in structural materials that resulted in failures, along with a description of the agents and conditions causing degradation, and design options currently used. For more examples for structures in a cold climate, see Reference [3], Appendix D.

Table D.1 — Environmental actions for structural materials and their control

Material	Environmental action	Action effects	Agents, conditions	Design options
Ground soil	Frost heave	Damage to foundation or fabric, floor slope	Fine-grained soils and ground temperature < 0 °C	Foundation location, type of soil
	Swelling and shrinkage of soils	Damage to foundation or fabric, floor slope	Expansive clays and changes in soil moisture content	—
Wood	Fungal decay	Loss of material, strength, appearance	Sustained moisture and oxygen with temperature ranging from 5 °C to 40 °C	Drainage (avoid water traps), preservatives, ventilation, naturally resistant species
	Subterranean termites	Loss of material, strength	Access from ground, oxygen, temperature > 5 °C	Preservatives, barriers, bait blocks
	Marine borers	Strength, loss of material	Salty or brackish water (e.g. piles)	Preservatives
	Drying shrinkage perpendicular to grain	Splitting, damage to other components, floor misalignment, nail popping	High initial moisture content, accumulated thicknesses perpendicular to grain (beams, stringers, plates)	Use dry wood, compatible materials, design to allow movement
Masonry: see table entries for stone, clay brick, concrete, concrete block and mortar, steel and stainless steel.				
Stone	Acid attack (leaching)	Disintegration, disfigurement	Carbonates in stone (e.g. limestone or sandstone), acid rain, lack of drainage, orientation	Choice of stone, pointing of mortar, protective coating
	Movements due to moisture change	Bowing of panels	Type of stone (marble), thickness	Use thicker section or stiff backing
Clay brick	Freeze-thaw	Spalling, disintegration	Lack of drainage, high moisture content during freeze-thaw cycles, aggravated by non-breathing surface coatings	Manufacturing process, drainage details, breathable coatings, moisture barriers, well-made (detailed to reduce water ingress) mortar joints
	Salt crystallization	Efflorescence, occasionally spalling	High moisture content and presence of salts in brick, mortar, or adjacent materials	Low salts in bricks and mortar, drainage details, well-made mortar joints
	Movements due to moisture or temperature variations	Cracking	Restraints	Movement joints

Table D.1 (*continued*)

Material	Environmental action	Action effects	Agents, conditions	Design options
Concrete, concrete block, and mortar	Freeze-thaw cycles	Disintegration, appearance	High moisture content during freeze-thaw cycles, aggravated by chlorides and lack of drainage	Air entrainment, mix design, choice of aggregates, drainage details
	Sulfate attack	Expansion followed by disintegration	Sulfates in groundwater, bricks, coal stockpiles or sea water	Type of cement, mix design, drainage, low sulfate in brick
	Alkali-aggregate reaction	Expansion followed by disintegration	Silica or dolomite aggregates, require moisture	Type of aggregate, type of cement (e.g. low alkali or composite cement) or cement additives, control of moisture
	Shrinkage	Cracking, damage of adjacent components (e.g. brick veneer)	High w/c ratio, high moisture content during construction (concrete blocks)	Mix design, construction sequence, control joints, reinforcement, curing and moisture control prior to use
	For chloride attack and carbonation, see “Steel” and “Corrosion of reinforcement in concrete.”			
Metals (all)	Galvanic corrosion	A wide variety of failures as defined in 6.6	Electrolyte (moisture-filled porous material), metals electrically connected	Choice of materials, electrical disconnection of adjoining metals
	Corrosion due to de-icing agents	Structural failure, unacceptable appearance	Presence of de-icing agents, humidity	Protective coatings, use of more corrosion-resistant metals
Steel	Corrosion in atmospheric environment	Connector failures, appearance, damage due to rust expansion	Sustained moisture, oxygen, aggravated by acid and hygroscopic impurities	Drainage (avoid water traps), ventilation, protective coatings
	Corrosion in marine environment	Corrosion of piles in splash zone	Sustained moisture, oxygen, aggravated by chlorides	Protective coating, cathodic protection
	Corrosion in soil environment	Pile failures, pipe failures	Sustained moisture, oxygen or anaerobic bacteria, aggravated by soluble salts, stray electric currents	Type of soil (test for resistivity, bacteria, etc.), protective coating, cathodic protection
	Corrosion of reinforcement in concrete environment	Loss of bond, failure of reinforcement, cracking and delamination of concrete	Sustained moisture, oxygen, chlorides or pH reduced by carbonation	Protective barriers, concrete mix, drainage details
	Corrosion of reinforcement in masonry environment	Failure of connectors, cracking of masonry	Sustained moisture, oxygen, aggravated by salts	Zinc coatings, stainless steel
	Corrosion in wood environment	Failure of connectors and surrounding wood	Sustained moisture, oxygen	Drainage (avoid water traps), ventilation, protective coatings
Weathering steel	Corrosion: atmospheric environment	Connection failures, damage due to rust	Retention of water between surfaces, sea water	Detailing to avoid accumulation of water between surfaces
Stainless steel	Pitting or crevice corrosion, intergranular corrosion, stress corrosion cracking	Connector failures	Type of stainless steel, aggravated by warm chlorinated atmospheres, high stress	Type of stainless steel
Aluminum alloys	Corrosion (dark pitted appearance	Downgrading of appearance, connector failures	Type of alloy, surface finish, contact with alkaline solution, contact with copper, copper-containing solution, or other metals	Drainage (avoid contact with alkaline solutions or damage from large dissimilar metal surface area), protective coatings

Table D.1 (*continued*)

Material	Environmental action	Action effects	Agents, conditions	Design options
Copper and alloys	Dezincification of brass	Failure of fasteners by loss of strength or cracking	Type of brass	Material selection (brass with less than 20 % zinc)
	Stress corrosion cracking (season cracking)	Failure of fasteners, cracking	High humidity, composition of brass	Annealing to reduce residual stresses
Glass	Thermal stress	Cracks starting at edge	Unequal solar heating (centre hot, edges cold); shadows, heat-absorbent glass, indoor heat	Avoid heat traps and strong shading; produce clean-cut edges or finish them well; heat strengthening
	Etching, leaching	Hazy appearance, milky or scummy deposit, darkening	Alkaline runoff from masonry or concrete; acid rain or water that leaches alkalis	Drain contaminated runoff away from glass
Polymers (natural and synthetic rubbers, sealants, roof membranes)	Chemical degradation, oxidation, ozonation	Loss of strength, cracking	Contact with oils and the atmosphere	Avoid contact with oils, selection of suitable synthetic rubber
Plastics, GRP (glass-fibre-reinforced polyester)	Moisture absorption	Fibre “pop-out”, loss of toughness	Presence of moisture	Drainage, cut edges should be sealed
GRP, other plastics, other FRP (fibre-reinforced plastic)	Chemical attack under tensile stress	Crazing and possible fracture	Exposure to solvents or contact with some sealants, tensile stresses	Avoid use of solvents, select compatible sealant
	Fatigue induced by temperature and moisture fluctuation	Surface cracking, degradation of mechanical properties	Exposure to temperature and humidity fluctuation, UV light	Surface protection from UV exposure
	Oxidation and photo-oxidation	Degradation of mechanical properties, discolouration, hazing, dullness	Exposure to UV light	Use of surface coating and/or UV absorber

Annex E
(informative)

Procedures for ensuring durability

Procedures for the design of structures for durability are contained in ISO 15686-1:2000, Clause 6. Detailed design procedures for ensuring durability are not given in this International Standard. Instead, Table E.1 recommends an example of procedures, including communication for quality assurance, for the design, construction, operation and maintenance of the structure during its service life, and for the investigation of damage due to degradation. The actual procedures, however, depend on local practice and type of facility.

Table E.1 — Example of procedures and communications for ensuring durability

Stage/activity	Procedures	Communicate with
Design for durability (designer) see ISO 15686-1	1) Establish design life of structure [a] and target probability of failure.	Owner
	2) Identify components likely to deteriorate during the design life of the structure, and design for access for inspection, maintenance, repair/replace [a] and ease of construction.	Contractors, fabricators, suppliers
	3) Establish the design life and target probability of failure for these components in accordance with Clause 8 [b].	
	4) Select materials with appropriate properties and avoid contact between incompatible materials [c].	Materials industry
	5) Detail to reduce agent accumulation [c] (see Annex C).	
	6) Make service-life predictions in accordance with Clause 9.	
	7) Prepare life-cycle cost/assessment [d] in accordance with ISO 15686-5 and ISO 15686-6 and, if necessary, revise the design [repeat (3) to (7)].	Owner/user
	8) Prepare a plan for inspection, maintenance, repair and replacement [e].	
	9) Prepare a plan for quality control during construction [f].	Contractor
Construction (contractor)	1) Review design (document review) and incorporate acceptable changes.	Designer
	2) Inspection and review of proposed changes by designer	Designer
	3) Ensure interaction of trades for ease of construction	Trades
	4) Ensure protection of components during construction	Supplier
Maintenance and operation (owner/user) see ISO 15686 (all parts)	1) Facility operations to control environmental influences inside (e.g. humidity, temperature) and outside (e.g. road salt) the facility	
	2) Implementation of maintenance plan, records	Designer
	3) Cleaning, repair and replacement	
	4) Inspections to verify or alter maintenance schedule	Investigator
Investigation of damage (investigator)	1) Assessment to determine cause of degradation [g]	Owner/user/designer
	2) Monitoring and testing	
	3) Recommendations	Owner
	4) Feedback for future practice (ISO 15686-7)	Profession

[a] To achieve the design life of a structure or a repair work, all details and components shall be designed for that life, with or without planned maintenance and repair; otherwise a replacement shall be planned and prepared for.

[b] Designs based on existing standards and proven design and construction practices are often recommended; see 9.1.

[c] There are a variety of measures that may be used to increase the service life, including selection of materials, providing barriers (e.g. zinc, special paints, anodic protection, preservative treatment of wood), detailing to minimize time of wetness (see Annex C) where exposure to environmental action is unavoidable (see Table D.1).

[d] Procedures for considering impacts to the environment (for sustainability) in the design of structures for durability are contained in ISO 15686-6.

[e] It is strongly recommended to prepare a maintenance/repair/replacement plan for the structure, including all the assumptions made in the design phase, for example the requirement for preventive maintenance such as inspection and cleaning to reduce cumulative damage, inspection, maintenance and repair of the structure, along with the protective and sheltering measures and replacement.

[f] Since the construction is very important for ensuring durability, it is recommended to prepare a plan for the quality control of the most important activities in construction, for example site inspection during construction by the designer, check of concrete cover, etc.

[g] For the determination of cause, the limit-states method (Figure 1) in reverse provides a useful tool:

damage (symptoms, Annex D); environmental action (Annexes B and D); transfer mechanisms (Annex C); structure environment (Annex B).

Bibliography

[1] ISO 9223:1992, *Corrosion of metals and alloys — Corrosivity of atmospheres — Classification*

[2] ISO 12944-2:1998, *Paints and varnishes — Corrosion protection of steel structures by protective paint systems — Part 2: Classification of environments*

[3] CSA S478-95, *Guideline for durability in buildings*

[4] CSA A370-04, *Connectors for Masonry*

[5] CAN/CSA A440.1-91, *Windows*

[6] ISO 22965-1, *Concrete — Part 1: Methods of specifying and guidance for the specifier*

[7] ISO 22965-2, *Concrete — Part 2: Specification of constituent materials, production of concrete and compliance of concrete*

[8] Leicester, R.H., Engineered durability for timber construction, *Progress in Structural Engineering and Materials,* 2(3), 2001

[9] Foliente, G.C., Leicester, R.H., Wang, C-H., MacKenzie, C. and Cole, I., Durability design for wood construction, *Forest Products Journal*, 52(1), p. 19, 2002

[10] Leicester, R.H., Wang, C.H., Nguyen, M.N., Foliente, G.C. and MacKenzie, C., Structural durability of timber in ground contact, *36th CIB W18 Meeting*, Estes Park, Colorado, USA, Paper 36-11-1, p. 10, August 2003

[11] Ang, A.H.S. and Tang, W.H., *Probability concepts in engineering: Emphasis on applications to civil and environmental engineering*, John Wiley & Sons, 2006

[12] Kasami, H., Izumi, I., Tomosawa, F. and Fukushi, I., Carbonation of concrete and corrosion of reinforcement in reinforced concrete, *Proc. of First Australia-Japan Coordinated Workshop on Durability of Reinforced Concrete,* Building Research Institute, Japan, C4, pp. 1-13, October 1986

[13] Fib, Model code for service life design, Bulletin no 34, 2006 1)

[14] Li, C.Q. Reliability-based service-life prediction of corrosion affected structures, *ASCE Journal of Structural Engineering*, pp. 1570-1577, October 2004

[15] ISO 15686-1:2000, *Buildings and constructed assets — Service life planning — Part 1: General principles*

[16] ISO 15686-2, *Buildings and constructed assets — Service life planning — Part 2: Service life prediction procedures*

[17] ISO 15686-3, *Buildings and constructed assets — Service life planning — Part 3: Performance audits and reviews*

[18] ISO 15686-7, *Buildings and constructed assets — Service life planning — Part 7: Performance evaluation for feedback of service life data from practice*

[19] ISO 15686-8, *Buildings and constructed assets — Service-life planning — Part 8: Reference service life and service-life estimation*

---

1) International Federation for Structural Concrete (fib), Case postale 88, CH-1015 Lausanne, Switzerland.

ICS 91.080.01

Price based on 39 pages