Aalto University
School of Engineering

Rak-43.3312 Repair Methods of Structures II

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Lecture 07: Service life of building structures

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Previous lecture summary

Lecture 01:

- Concrete repairs – Standards
  - EN 1504 covers the whole concrete repair process, from the initial identification of a problem, through to the works on site.

Lecture 02:

- Demolition planning
- Demolition methods applicable for concrete repair
- Controlling risks in demolition work

Lecture 03:

- Corrosion protection of reinforced concrete
- Corrosion prevention methods

Lecture 04:

- Planning of the repair project
- Repair methods for concrete facades and balconies, and rendered structures

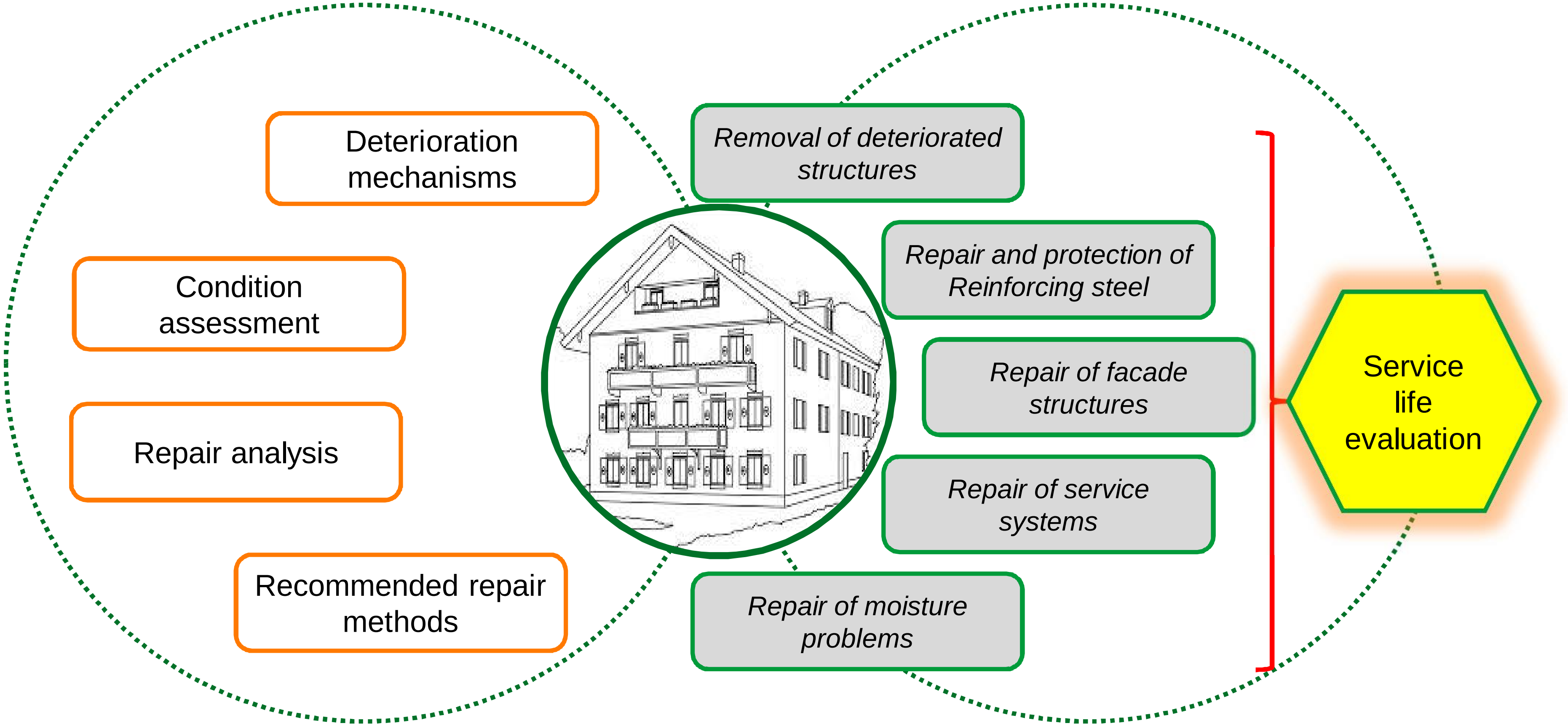
Lecture 05:

- Energy consumption in residential buildings
- Energy renovation methods

Lecture 06:

- Repair methods for buildings having indoor air problems
- Classification and examination of the suitable repairing methods

Course content



Deterioration mechanisms

Condition assessment

Repair analysis

Recommended repair methods

Removal of deteriorated structures

Repair and protection of Reinforcing steel

Repair of facade structures

Repair of service systems

Repair of moisture problems

Service life evaluation

Rak-43.3301 Repair Methods of Structures I

Rak-43.3312 Repair Methods of Structures II

Outlines

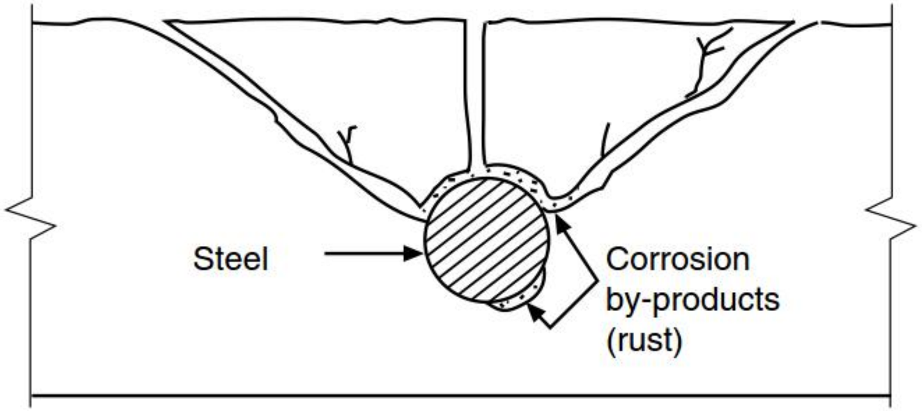
- Deterioration processes and loss of function
- Life of building constructions
- Durability design of concrete structures
- Modelling of the service life for concrete structures
- Estimating residual service life of deteriorated reinforced concrete structures

Deterioration processes
and
loss of function

Deterioration processes

- Deterioration is due to the presence of water either in liquid or solid (ice) form which is transported into the concrete through cracks.
- Cracks are created or widened by (not counting cracks due to structural stress)
  - **freeze/thaw**,
  - **carbonation induced corrosion** and
  - **chloride induced corrosion**

Corrosion of embedded metals



The expansion of corroding steel creates tensile stresses in the concrete, which can cause cracking, delamination, and spalling.

Deterioration processes

- Carbonation lowers the pH value of the concrete, enabling corrosion of the reinforcement if water is present.
- The process can be accelerated if chloride is available, which acts as catalyst.
- Corrosion of embedded metals in concrete can be greatly reduced by sufficient concrete cover

Minimum Concrete Cover Requirements (ACI 318)

Concrete structure	**Minimum cover depth [mm]**
Concrete cast against and permanently exposed to earth	75
Concrete exposed to earth or weather	50
Concrete not exposed to weather or in contact with ground (slabs, walls, beams, columns)	40
Concrete not exposed to weather or in contact with ground (Shells, folded plat members)	20

Deterioration processes

- Freeze/thaw produces pressure in the capillaries and pores of the concrete if water is expanding due to freezing.
- If the pressure exceeds the tensile strength of the concrete, the cavity will dilate and rupture.
- The accumulative effect of successive freeze-thaw cycles and disruption of paste and aggregate can eventually cause significant expansion and cracking, scaling, and crumbling of the concrete

- The resistance of concrete to freezing and thawing in a moist condition is significantly improved by the use of intentionally entrained air
- Target air contents for frost-resistant concrete (ACI 318)

Nominal Maximum aggregate size [mm]	**Air Content, %**	
	Severe exposure	**Moderate exposure**
9	7.5	6
13	7	5.5
19	6	5
25	6	4.5
37.5	5.5	4.5

End of life due to deterioration

- Material (or combination of materials) related parameters affect its (their) deterioration
- To start deterioration in a material, several deterioration agents (parameters) are needed.
- For such materials it is necessary to determine the parameters that influence the deterioration process and the effect of their combination.

- Parameters could be a combination of temperature, moisture content, pH value etc.
- Exceeding a set of critical values will mean the end of the life for the examined construction.
- For most materials, a longer exposure to a deterioration parameter will result in a more advanced deterioration.

Life of building constructions

What is Service Life?

Service life (of building component or material) is the period of time after placement of concrete, during which all the properties exceed the minimum acceptable values when routinely maintained.

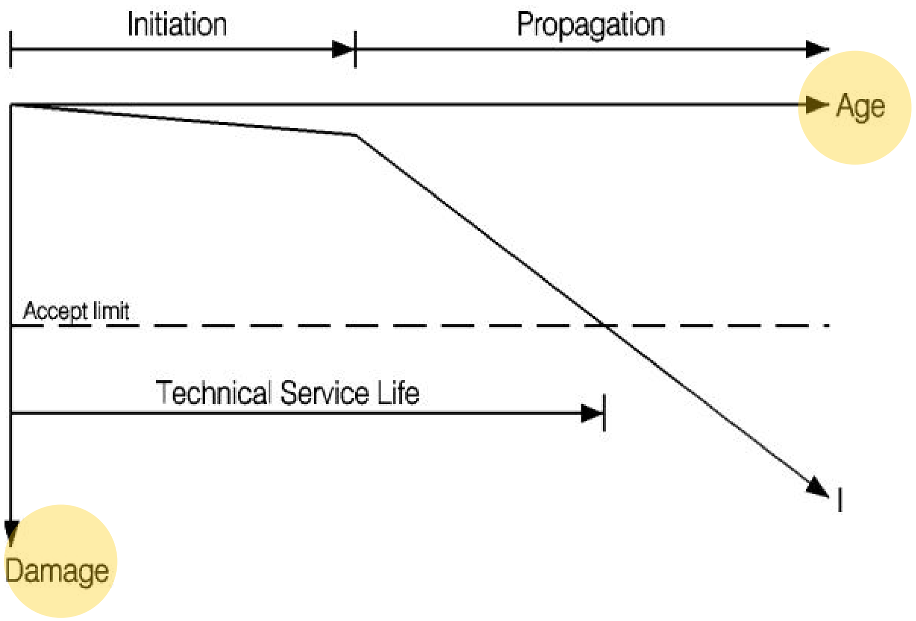
Three types of service life have been defined:

1. **Technical service life:** is the time in service until a defined unacceptable state is reached, such as spalling of concrete, safety level below acceptable, or failure of elements.
2. **Functional service life:** is the time in service until the structure no longer fulfills the functional requirements or becomes out of date due to change in functional requirements
3. **Economic service life:** is the time in service until replacement of the structure (or part of it) is economically more expensive than keeping it in service.

ACI 365.1**R-00, “Service-Life Prediction - State-of-the-Art Report”,** standard by American Concrete Institute

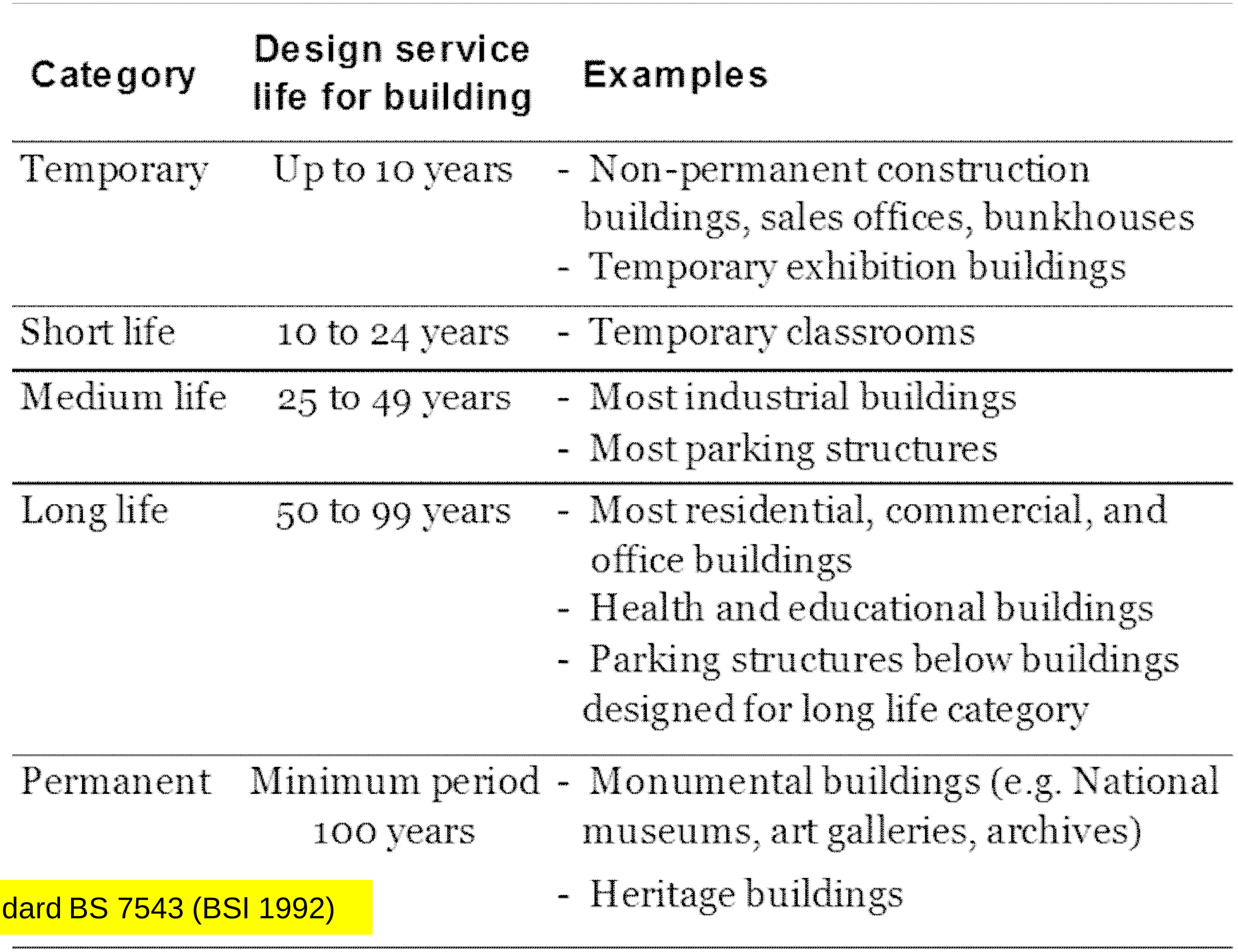
What is Service Life?

- Service life is the sum of **initiation** and **propagation** periods
- The initiation period of damage is the time needed for the damage to start. For example the time for the carbonation or chlorides ingress needed to initiate corrosion of the reinforcing
- The propagation period of damage is the time between first damage and the time to repair



Technical service life

Categories of design service life for buildings



Category	Design service life for building	Examples
Temporary	Up to 10 years	- Non-permanent construction buildings, sales offices, bunkhouses - Temporary exhibition buildings
Short life	10 to 24 years	- Temporary classrooms
Medium life	25 to 49 years	- Most industrial buildings - Most parking structures
Long life	50 to 99 years	- Most residential, commercial, and office buildings - Health and educational buildings - Parking structures below buildings designed for long life category
Permanent	Minimum period 100 years	- Monumental buildings (e.g. National museums, art galleries, archives) - Heritage buildings

British standard BS 7543 (BSI 1992)

Durability design of concrete structures

Durability design of concrete structures

Aspects that need to be considered (Deterioration parameters):

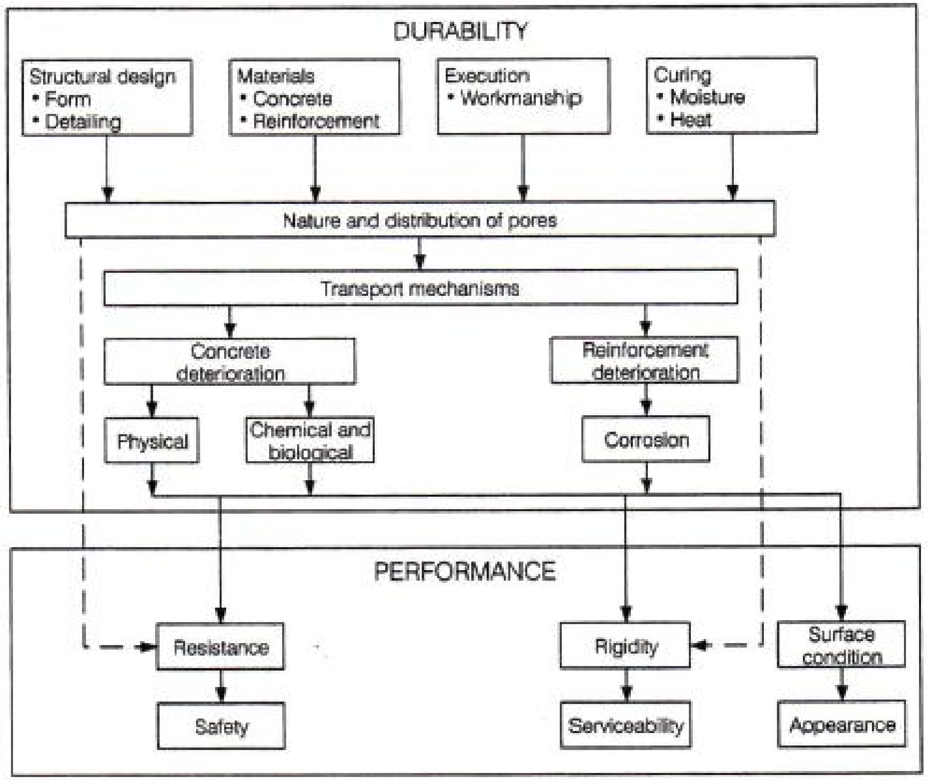
a) Environment / exposure conditions

b) Deterioration mechanisms for concrete and reinforcement

c) Cover thickness

d) Penetrability of concrete cover layer

e) Service life: Period in which structure has adequate resistance to withstand environmental actions that cause deterioration



Environment / exposure conditions

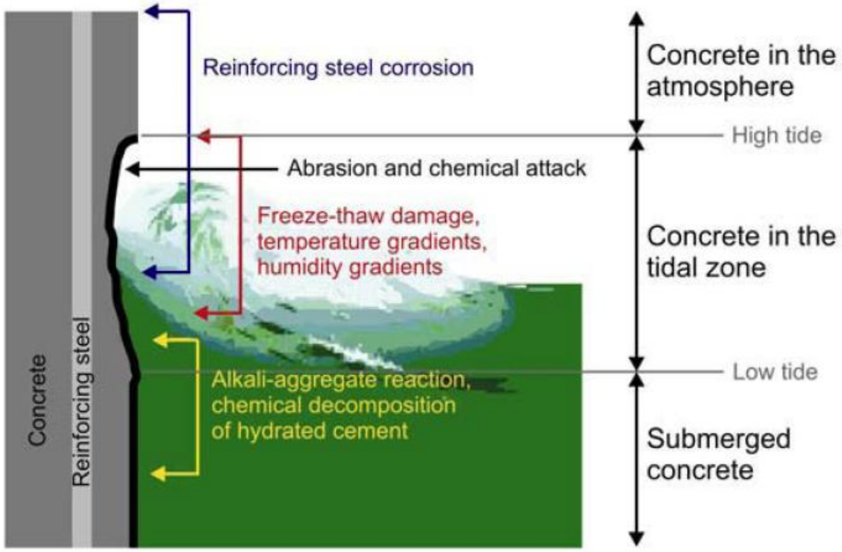
- Determination of the exposure conditions is very import with respect to service life design
- The exposure conditions:
  - Temperature
  - Rainfall
  - wetting events
  - freeze thaw cycles
  - relative humidity and
  - CO_2 content

Climate	Horizontal extension	Vertical extension
Regional climate	1-200 km	1 m -100 km
Local climate	100 m - 10 km	0.1 m - 1 km
Near surface and surface climate	0.01 - 100 m	0.01 - 10 m

DURACRETE:
The European Union – Brite EuRam III
Models for Environmental Actions on Concrete Structures

Environment / exposure conditions

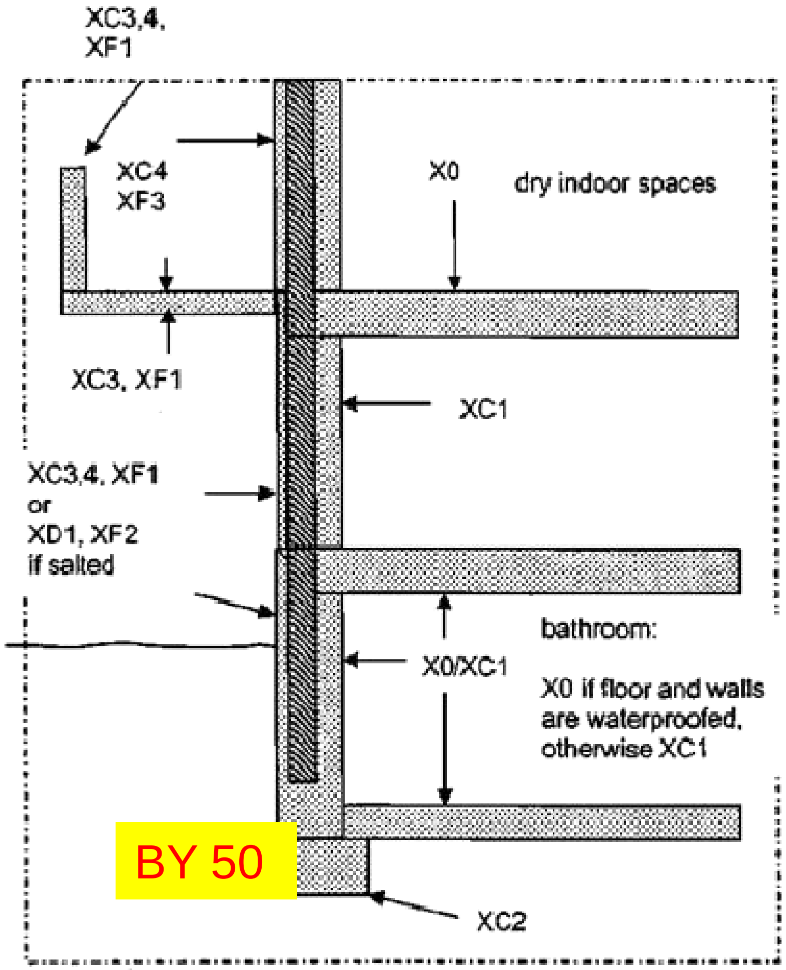
- Different parts of a structure may be in different exposure conditions (exposure classes).
- Examples are:
  - the submerged, the tidal, the splash and the atmospheric zones of a marine structure
  - different geographic orientations - north / south / east / west
  - Seaward / landward orientation
  - very local differences can be taken into account such as vertical faces, horizontal surfaces facing upward (risk of ponding) or facing downward.



Malhorta, V.M., Durability of Concrete, Corrosion Handbook Second Edition, R.W. Revie Ed., Wiley, 2000

Exposure classes

EN 206-1, Concrete: Specification, performance, production & conformity



Class	Corrosion induced by	Sub-classes	Description of the environment
X0	No risk		Very dry
XC	Carbonation	XC1	Dry or continuously wet
		XC2	Moist, rarely dry.
		XC3	Moderately moist
		XC4	Periodical wetting and drying
XF	Freeze-thaw attack	XF1	Moderate saturation with water without thawing agents
		XF2	Moderate saturation with water and di-icing agents
		XF3	High saturation with water without de-icing agents
		XF4	High saturation with water and de-icing agents

Exposure classes

EN 206-1, Concrete: Specification, performance, production & conformity

Class designation	Description of the environment	Informative examples where exposure classes may occur
Corrosion induced by chlorides		
XD1	Moderate humidity	Concrete surfaces exposed to airborne chlorides
XD2	Wet, rarely dry	Swimming pools Concrete components exposed to industrial waters containing chlorides
XD3	Cyclic wet and dry	Parts of bridges exposed to spray containing chlorides Pavements Car park slabs
Corrosion induced by chlorides from sea water		
XS1	Exposed to airborne salt but not in direct contact with sea water	Structures near to or on the coast
XS2	Permanently submerged	Parts of marine structures
XS3	Tidal, splash and spray zones	Parts of marine structures
Chemical attack		
XA1	Slightly aggressive chemical environment according to EN 206-1, Table 2	Natural soils and ground water
XA2	Moderately aggressive chemical environment according to EN 206-1, Table 2	Natural soils and ground water
XA3	Highly aggressive chemical environment according to EN 206-1, Table 2	Natural soils and ground water

Modelling of the Service life for Concrete structures

Service life prediction approaches

To predict service life, the following facts must be known:

A. the mechanisms governing the initiation and stable propagation stages,

B. the relevant parameters involved in the mechanisms, and

C. the present state of the reinforced concrete.

Prediction approaches have been classified into the following different categories:

1) estimations based on experience,
2) deductions from performance of similar materials,
3) estimations based on accelerated testing,
4) mathematical modeling based on the degradation processes, and
5) application of some other concepts, such as reliability and stochastic methods, etc.

Probabilistic service life design

R(t) > S(t) or

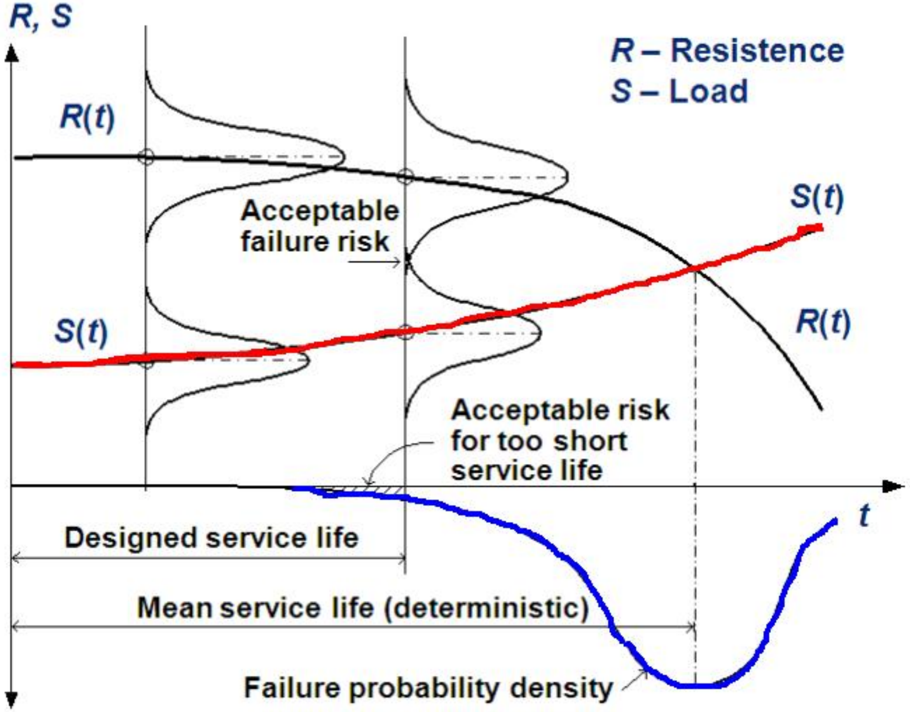
g = R(t) - S(t) > 0

Where:

R(t) indicates the resistance variable over time

S(t) represents the load variable and over time

g is the limit state function.



Probabilistic service life design

the failure probability (P_f) can be calculated as shown below;

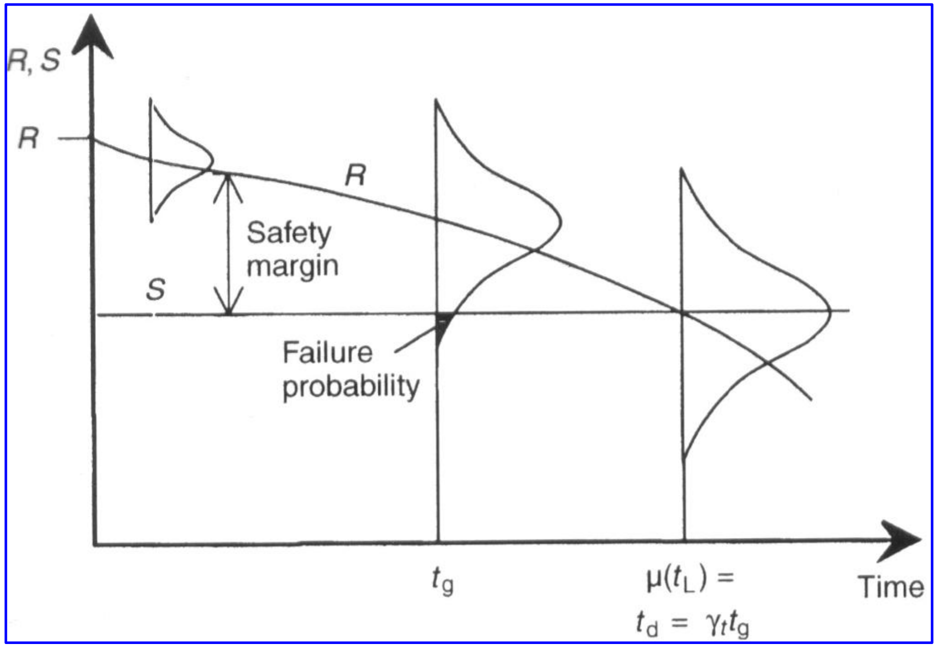
$P_f = P[R - S < 0]$ or

$P_f(t) = P[R(t) < S(t)]$

From the durability point of view, the resistance of the structure R(t) may decrease with time.

The load parameter S(t), however, can remain constant or increase with time.

Because the resistance R(t) decreases and the load effect S(t) increases with time, the failure of probability increases with time



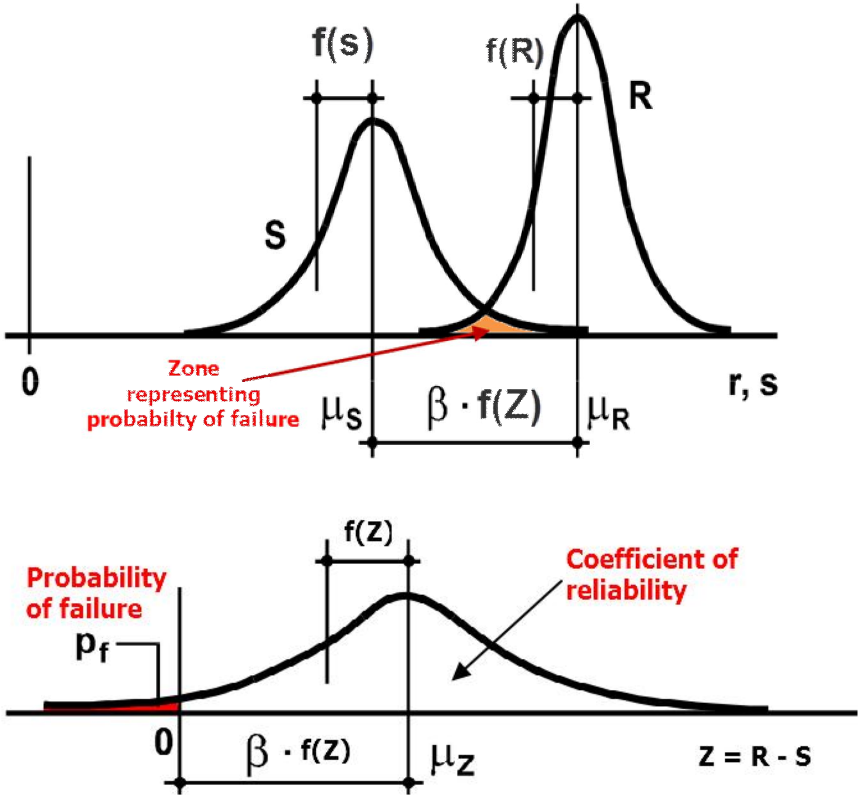
Probabilistic service life design

Failure probability (Pf)

$$Pf = \Phi\left(-\frac{\mu(Z)}{f(Z)}\right) = \Phi\,(-\beta)$$

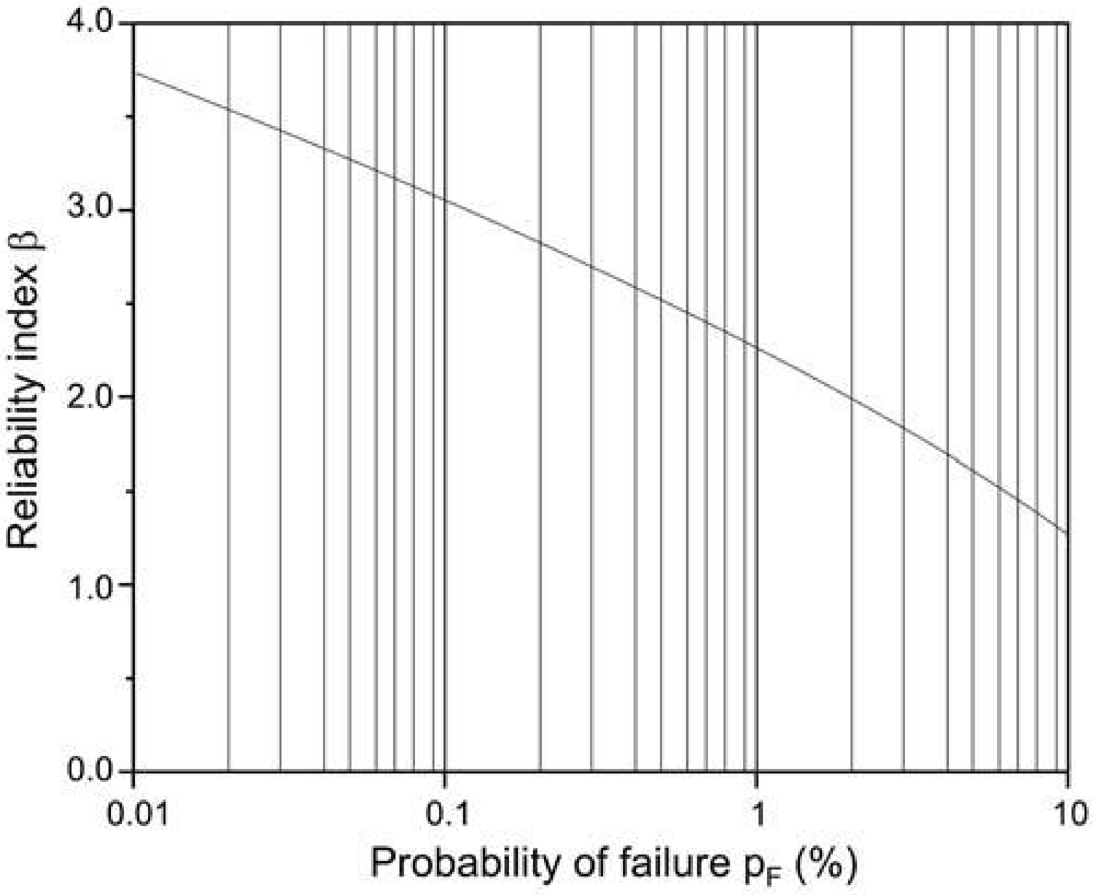
Φ [-] normal distribution

β Is the reliability index



Probabilistic service life design

Relationship of failure probability p_f and reliability index β for a normal distributed reliability function.



Ferreira, R.M. (2004), Probability-based durability analysis of concrete structures in marine environments

The corrosion of reinforcement in concrete

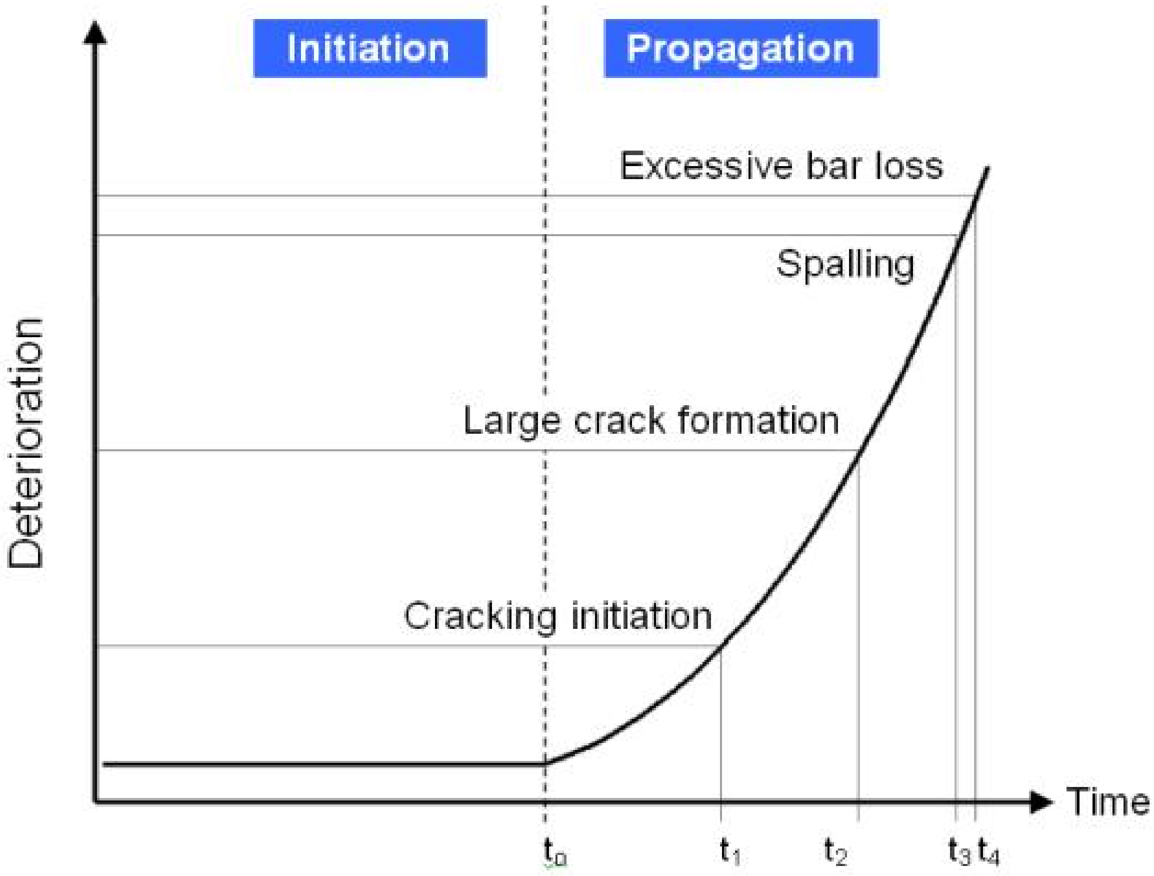


Figure 3.1 Simple two-stage model of deterioration of reinforced concrete [Blin et al. 2008]

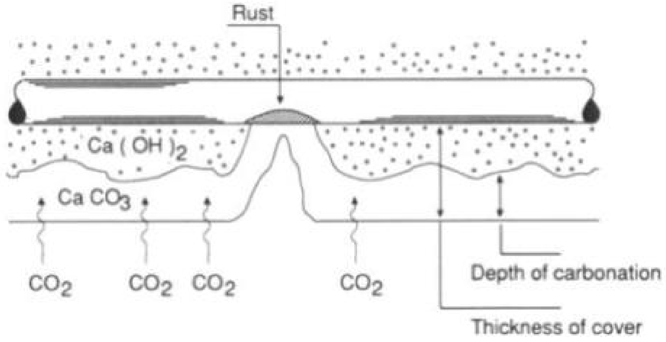
Initiation: Carbonation induced corrosion

p{failure} = $p_f = p\{d_c - x_c(t) < 0\}$

- p_f: failure probability [%]
- d_c: concrete cover [mm]
- x_c (t): carbonation depth at the time t [mm]
- t: age of the structure [a]

$Xc(t) = K_{ca}\sqrt{t}$

- K_{ca} is the coefficient of carbonation [mm/$a^{0.5}$], ‘K_{ca}’ based on concrete quality, aggregate types, exposure conditions, and moisture content.
- t: is age of the structure [a]



Initiation: Carbonation induced corrosion

$$X_{\mathrm{ca}} = k_{\mathrm{con}} * k_{\mathrm{cur}} * k_{\mathrm{T}} * k_{\mathrm{RH}} * k_{\mathrm{CO}_2} * \sqrt{t}$$

where

k_{con}	is the quality of concrete related coefficient,
k_{cur}	is the concrete curing factor,
k_{RH}	is the relative humidity related coefficient,
k_{T}	is the temperature related coefficient, and
k_{CO2}	is the square root of the carbon dioxide content in air.

w = water amount [kg]
c = cement amount [kg]
a = aggregate amount [kg]

$$k_{\mathrm{con}} = 350 * \frac{\rho_c}{\rho_w} * \left(\frac{\frac{w}{c} - 0.3}{1 + \frac{\rho_c}{\rho_w} * \frac{w}{c}} \right) * \sqrt{1 + \frac{\rho_c}{\rho_w} * \frac{w}{c} + \frac{\rho_c}{\rho_a} * \frac{a}{c}}$$

where

ρ_c	is the mass density of the cement [kg/m³],
ρ_w	is the density of the water [kg/m³],
ρ_a	is the mass density of the aggregates [kg/m³],
w/c	is the water-to-cement ratio [-], and
a/c	is the aggregate-to-cement ratio [-].

Al-Neshawy, F. (2013), Computerised prediction of the deterioration of concrete building facades caused by moisture and changes in temperature

Initiation: Carbonation induced corrosion

$$k_{\mathrm{T}} = EXP\left(\frac{Q}{R} * \left(\frac{1}{273 + T_0} - \frac{1}{273 + T}\right)\right)$$

where

Q	is the activation energy of the carbonation process, Q = 2.7 [kJ/mol]
R	is the gas constant, R = 0.008314 [kJ/mol.K]
To	is the reference temperature, To = 25 [°C]
T	is the actual temperature in the concrete [°C].

$$k_{\mathrm{RH}} = \left(1 - \frac{RH}{100}\right)^n \; for\ RH \geq 65\%$$

Where:

RH	is the relative humidity in the concrete cover [%],
n	is an exponent of range (1 – 2.5)

The carbon dioxide content of the atmosphere by volume is considered to be 0.035% (350 ppm) and the value of k_{CO2} is considered to be 0.0187.

Al-Neshawy, F. (2013), Computerised prediction of the deterioration of concrete building facades caused by moisture and changes in temperature

According to Duracrete (2000), the values of the concrete curing coefficient (k_{cur}) for the carbonation resistance are 1.0 for 7 days' curing and 0.76 for 28 days' curing of the concrete

Initiation: Carbonation induced corrosion

The initiation time for corrosion as a result of carbonation ($t_{ca,\ init}$) is the period required for the carbonation front to reach the reinforcement rebar.

$$t_{ca,\ init} = \left(\frac{x}{K_{ca}}\right)^2$$

- x the concrete c over depth [mm]
- K_{ca} is the coefficient of carbonation [mm/a$^{0.5}$]

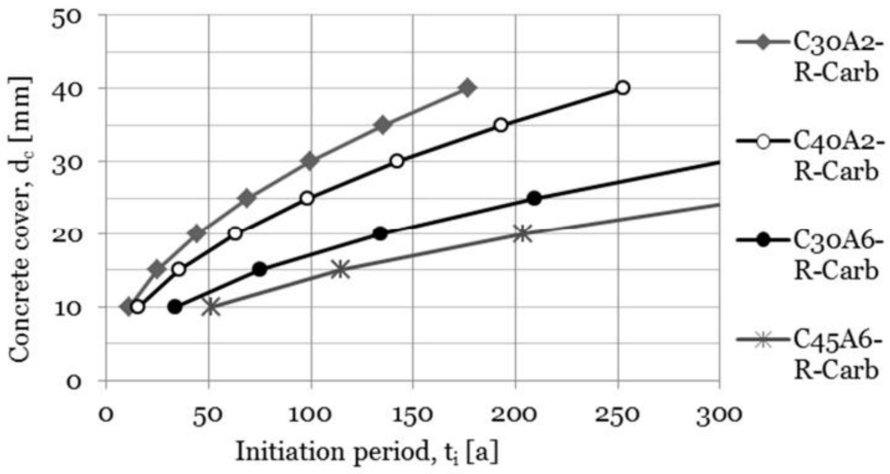


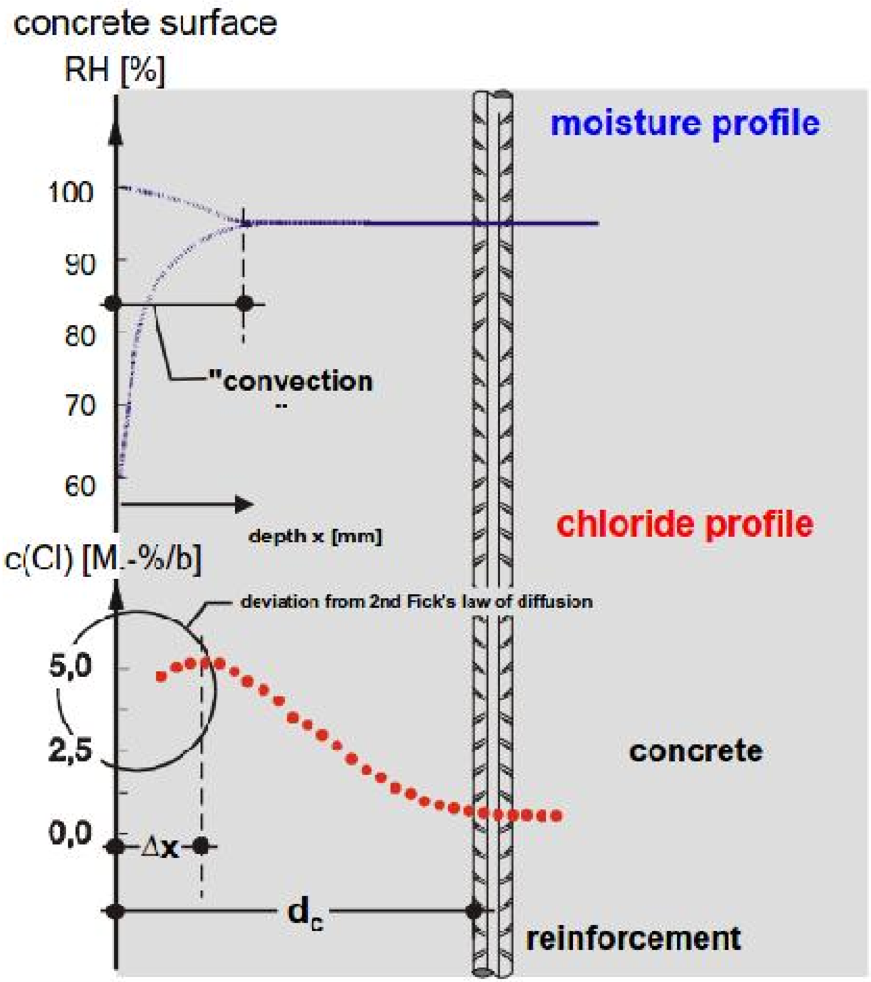
Figure 6.11: Initiation time of corrosion resulting from carbonation.

Al-Neshawy, F. (2013), Computerised prediction of the deterioration of concrete building facades caused by moisture and changes in temperature

Initiation: Chloride induced corrosion

$p\{\text{failure}\} = p_f = p\ \{C(_{x,t}) \geq C_{crit}\}$

- p_f: failure probability [%]
- C_{crit} is the critical chloride concentration representing the barrier effect (Chloride threshold)
- $C_{(x,t)}$ is the chloride concentration at depth and time



Initiation: Chloride induced corrosion

diffusion process, based on Fick's second law, can be used to model the time for chloride to reach and initiate corrosion

$$C_{(x,t)} = C_0\left\{1 - erf\left(\frac{x}{2\sqrt{D\,t}}\right)\right\}$$

- $C_{(x,t)}$ is the chloride concentration at depth and time
- C_o the surface chloride concentration,
- D the diffusion coefficient,
- t the time for diffusion,
- x the concrete cover depth, and
- erf is the statistical error function.

Corrosion initiation time which is the time required by chloride content at rebar depth to reach threshold value, can be evaluated using:

$$t_{cl,\ init} = \frac{x^2}{4D}\sqrt{\frac{1}{erf}\left(1 - \frac{c_0}{c_{(x,\ t)}}\right)}$$

$$\operatorname{erf}(x) = \frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2}\,dt.$$

http://mathworld.wolfram.com/Erf.html

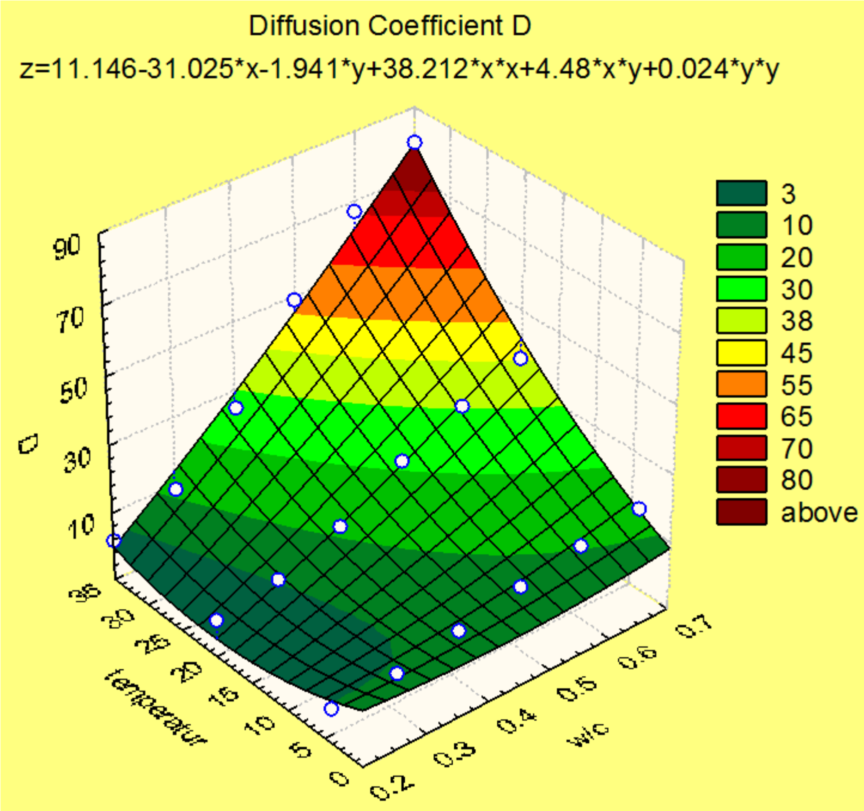
Initiation: Chloride induced corrosion

The **surface chloride content** and rate of its build-up is determined from the type of structure (e.g. bridge deck, car park), the type of exposure (e.g. marine, de-icing salts)

Exposure condition	Surface chloride level	
	(by wt of concrete)	(by wt of cement)
Marine splash zone	0.8% instantaneously	5.0% instantaneously
Marine spray zone	1.0% over 10 years	6.25% over 10 years
Up to 800m from the sea	0.6% over 15 years	3.75% over 15 years
800m – 1.5km from the sea	0.6% over 30 years	3.75% over 30 years
Parking structures	0.8-1.0%	5.0-6.25%

Initiation: Chloride induced corrosion

- The time to corrosion imitation is inversely proportional to the diffusion coefficient D.
- The diffusion coefficient D is not a real physical constant for a given concrete structure, since it depends on a number of physical factors.
- The most important factors are the water/cement ratio w/c, the temperature, and the amount of e.g. silica fumes



The diffusion coefficient *D* (10^{-12} m^2/s) as a function of *w/c* and of the temperature

Thoft-Christensen, P. Stochastic Modelling of the Diffusion Coefficient for Concrete. Proceedings of IFIP Conference on Reliability and Optimization of Structural Systems, Osaka, Japan, 2002, pp.151-159.

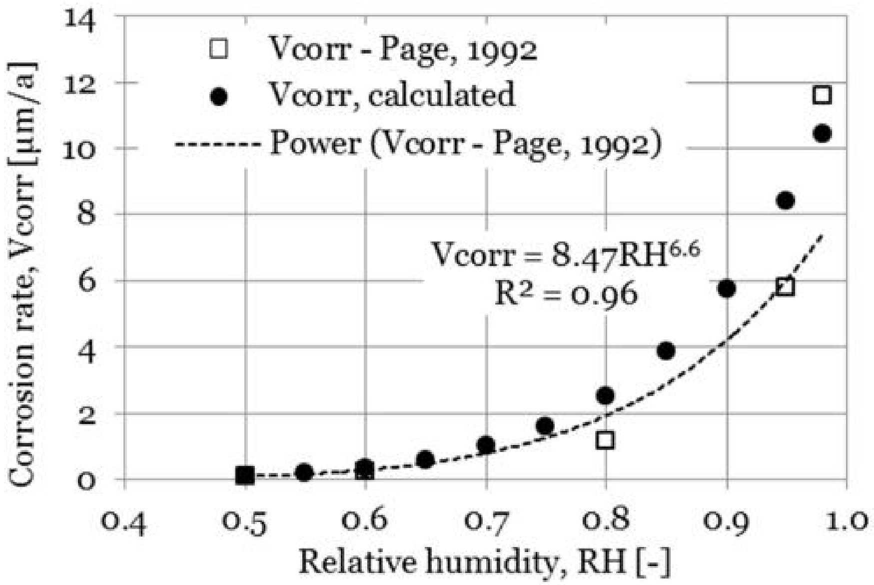
Corrosion propagation time

The propagation time is the time between the initiation of corrosion and the moment when visible cracks appear along the reinforcement (e.g. crack widths greater than 0.3 mm)

$$t_p = \frac{80}{\phi} * \left(\frac{d_c}{V_{corr}}\right)$$

where

t_p	is the propagation time [a],
V_{corr}	is the corrosion rate [μm/a],
d_c	is the cover thickness [mm], and
ϕ	is the diameter of the reinforcement [mm]



$$V_{corr} = 12.0 * \left(\frac{RH}{100}\right)^{7.0}$$

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The frost damage model

The model involves the effect of

- the entrained air content,
- the water-to-cement ratio,
- the number of freezing-thawing cycles

on the relative dynamic modulus of elasticity of the concrete.

$$C_a = \begin{cases} 275 * w_a + 118.25 * w_a^2 & for\ w_a \geq 4\% \\ 118.25 * w_a^2 & for\ w_a < 4\% \end{cases}$$

where
w_a is the air content of the fresh concrete [%]

$$C_b = 4.2 - 8.0 * \left(\frac{w}{c}\right) + 3.2 * \left(\frac{w}{c}\right)^2$$

where
w/c is the water-to-cement ratio [-]

$$Calculated\ RDM = 100 - \left(\frac{N_{FT}}{C_a * C_b - 100}\right) * 100$$

where
N_{FT} is the number of freezing-thawing cycles [cycle],
C_a is a coefficient dependent on the air content [-], and
C_b is a coefficient dependent on the water-to-cement ratio [-]

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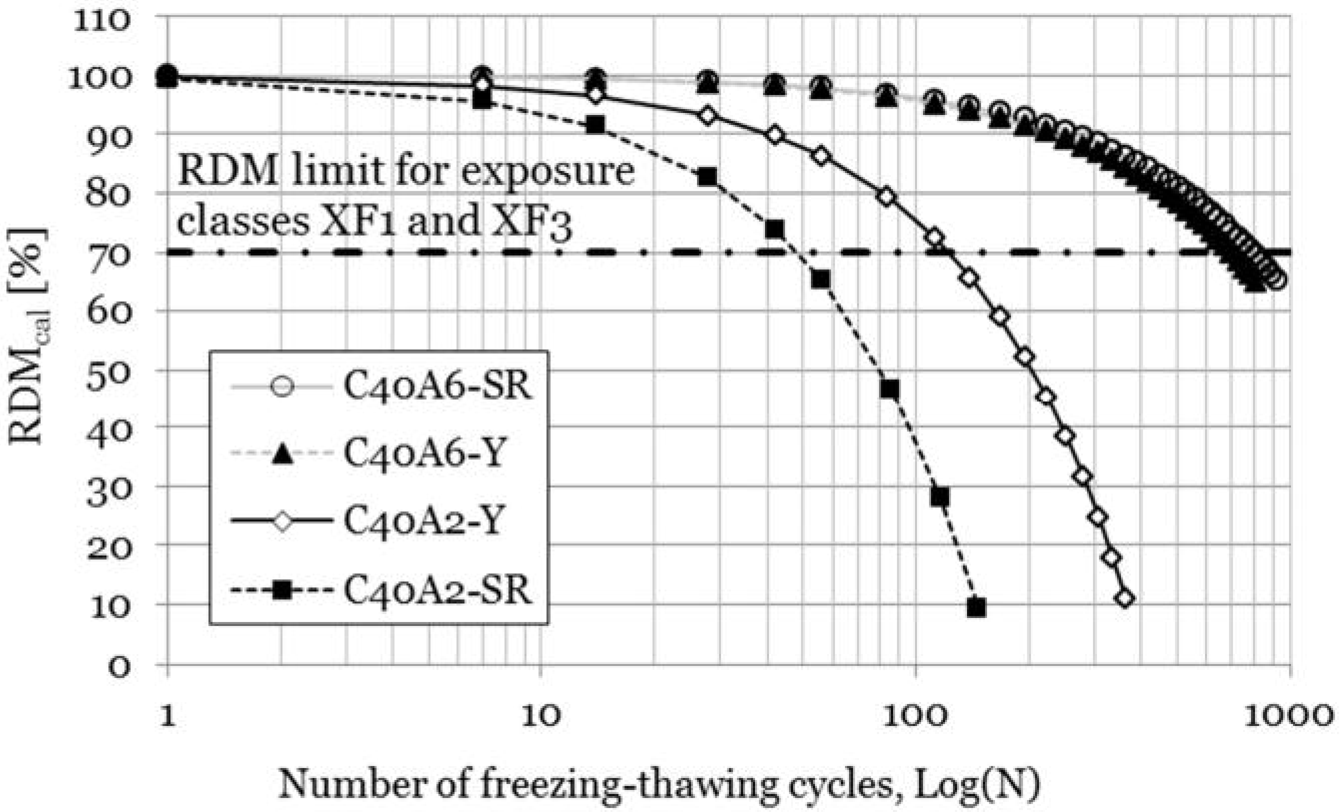
The frost damage model

Calculated RDM for different air-entrained and non-air-entrained concretes → total freezing-thawing cycles at 70% RDM



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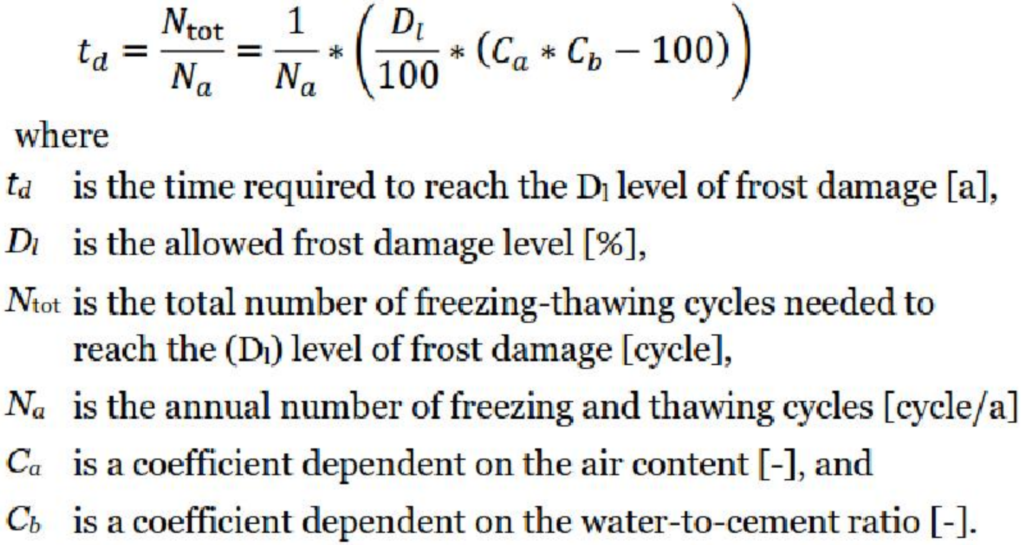
The frost damage model

- The frost damage level is taken as the point of significant cracking and deterioration of the concrete as a result of freezing-thawing action
- The minimum critical level of RDM to ensure the satisfactory performance of the structure under cyclic freezing and thawing action is RDM level of 70%
- In Finland, 15 cycles is considered as the annual number of freezing and thawing events



$$t_d = \frac{N_{tot}}{N_a} = \frac{1}{N_a} * \left(\frac{D_l}{100} * (C_a * C_b - 100)\right)$$

where

t_d	is the time required to reach the D_l level of frost damage [a],
D_l	is the allowed frost damage level [%],
N_{tot}	is the total number of freezing-thawing cycles needed to reach the (D_l) level of frost damage [cycle],
N_a	is the annual number of freezing and thawing cycles [cycle/a]
C_a	is a coefficient dependent on the air content [-], and
C_b	is a coefficient dependent on the water-to-cement ratio [-].

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The frost damage model

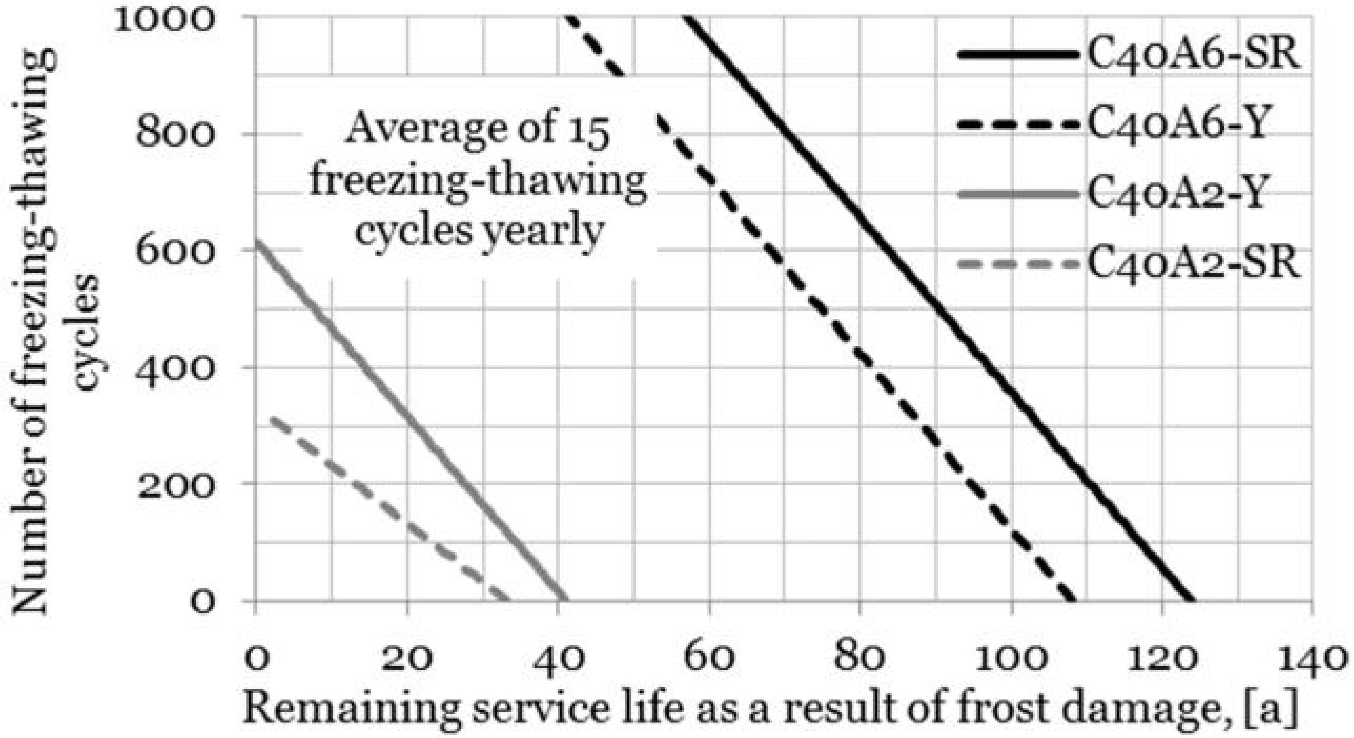


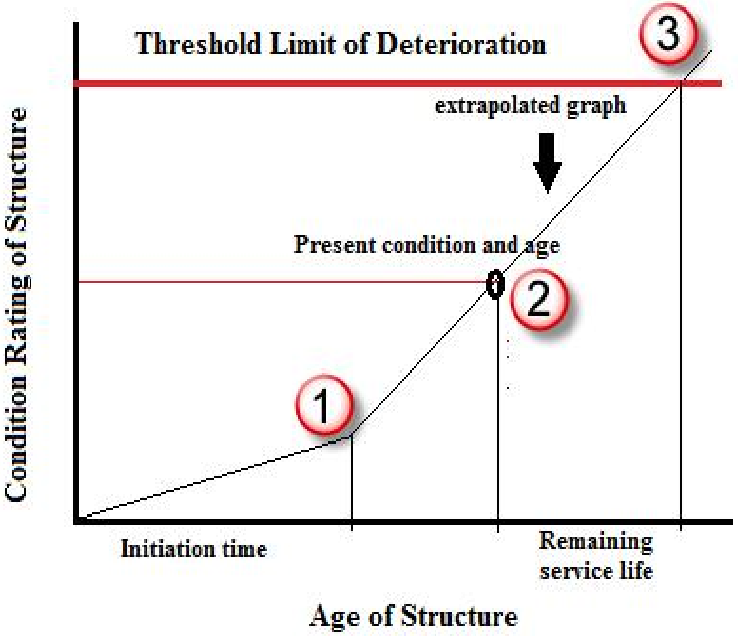
Figure 6.21: The remaining time of the concrete structures before they reach a frost damage deterioration level of 30%.

Al-Neshawy, F. (2013), Computerised prediction of the deterioration of concrete building facades caused by moisture and changes in temperature

Estimating residual service life of deteriorated reinforced concrete structures

Estimating residual service life

Rate	Failure Extent
0	safe
1	good
2	low risk but satisfactorily
3	fair
4	Moderate risk
5	poor
6	High risk
7	Serious risk
8	critical
9	failure



- Calculate the initiation time for deterioration, the plot the point (1) using a failure extent rate 1
- Based on the condition survey (failure extent rate) and the present age of the structure, plot point (2)
- Extrapolate the line graph and plot the point (3) using failure extent rate 9
- Estimate the remaining service life of the concrete structure

http://pubs.sciepub.com/ajcea/1/5/1/index.html

Estimating residual service life

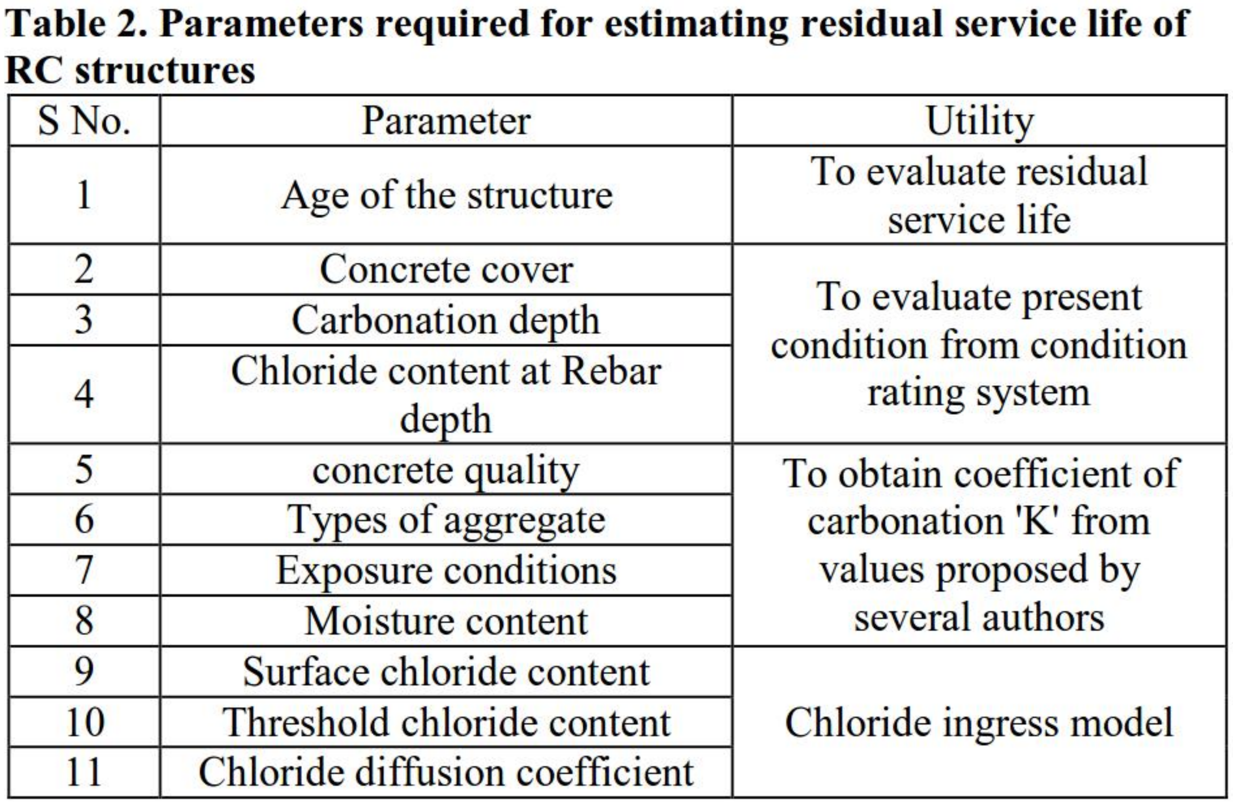


Table 2. Parameters required for estimating residual service life of RC structures

S No.	Parameter	Utility
1	Age of the structure	To evaluate residual service life
2	Concrete cover	To evaluate present condition from condition rating system
3	Carbonation depth	
4	Chloride content at Rebar depth	
5	concrete quality	To obtain coefficient of carbonation 'K' from values proposed by several authors
6	Types of aggregate	
7	Exposure conditions	
8	Moisture content	
9	Surface chloride content	Chloride ingress model
10	Threshold chloride content	
11	Chloride diffusion coefficient	

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Estimating residual service life

Examples of concrete mix design

Concrete	Concrete composition [kg/m³]					Air content
	Cement*	Water	W/C	Agg.	Air agent	
C25A2	200	180	0,90	1963	0,0	2,0
C40A2	280	180	0,64	1894	0,0	2,0
C25A3	250	190	0,76	1867	0,0	2,8
C25A4	250	190	0,76	1815	0,1	4,3
C45A6	475	190	0,40	1610	0,4	5,9
C40A7	475	190	0,40	1557	0,7	6,8
*) Cement type: Rapid cement [CEM II A 42.5 R]						

Al-Neshawy, F. (2013), Computerised prediction of the deterioration of concrete building facades caused by moisture and changes in temperature

Summary

Teaching event summary

- Deterioration processes and loss of function
- Life of building constructions
- Durability design of concrete structures
- Modelling of the service life for concrete structures
- Estimating residual service life of deteriorated reinforced concrete structures

Next teaching events

- Preparing for the assignment seminar