Establishing links between performance-based durability design and sustainability

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Presentation overview

Contents

Durability design/specification (with an eye on sustainability):

- Prescriptive approach
- Performance-based approach
  - ➢Deemed-to-satisfy approach
  - ➢Full- probabilistic approach
  - ➢Comparison of results

Links between durability and sustainability

Introduction

Prescriptive specifications do not adequately address sustainability issues

- ❑ Do not have the flexibility in addressing new or marginal materials
- ❑ Conservative approach – may result in resource waste
- ❑ Danger of under-specification for severe environments leading to premature failure
- ❑ No means to check actual specification requirements, in particular the as-built quality

Introduction

Consequences:

- The resulting concrete is ‘indeterminate’ (in the sense that we do not really know what we have got)
- It may actually be inadequate to the task, thus requiring repair and maintenance during the structure’s service life resulting in:
  - Unanticipated material consumption
  - Social disruptions

Introduction

- On the other hand, it may be over-conservative
- The irony is that, while many current durability specifications are viewed as being over-conservative, we have the phenomenon of a massive stock of under-performing infrastructure in respect of longevity and durability
- This is simply ‘un-sustainable’

Performance-based Durability Design and Specification

Performance-based design

Performance-based design and specifications limit the environmental consequences on the structure to defined acceptable levels (targets) during the structure's service life (e.g. a pre-defined level of deterioration or state of repair)

Performance-based design

General framework for performance-based design:

1. **A Robust Quality Control Test (or Tests)**

   Routine, easily-carried out, reliable measures of resistance to deterioration (e.g. to chloride ingress)

2. **A Service Life Model**

   This must relate performance to the quality control test (e.g. in terms of limiting material parameters)

3. **Able to account for Differences** (i.e. 'Margins') **between 'Material Potential' and 'As-Built' Values**

   In order to differentiate between areas of responsibility (e.g. material supplier & constructor)

Next section illustrates the above with reference to SA developments

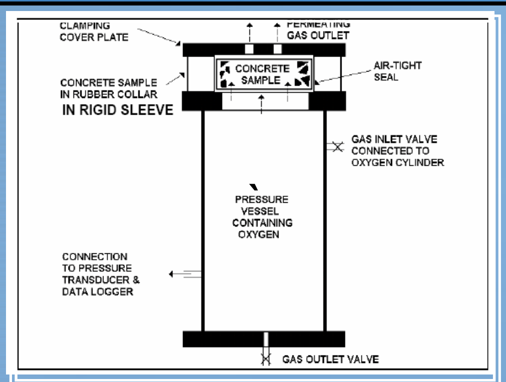
Performance-based design

1) Quality control tests:

– the approach developed in SA is that of *durability index (DI) tests* which serve as practical tools for durability studies, and to characterize the resistance of concrete to ionic or molecular transport

1. Chloride conductivity

2. Water sorptivity



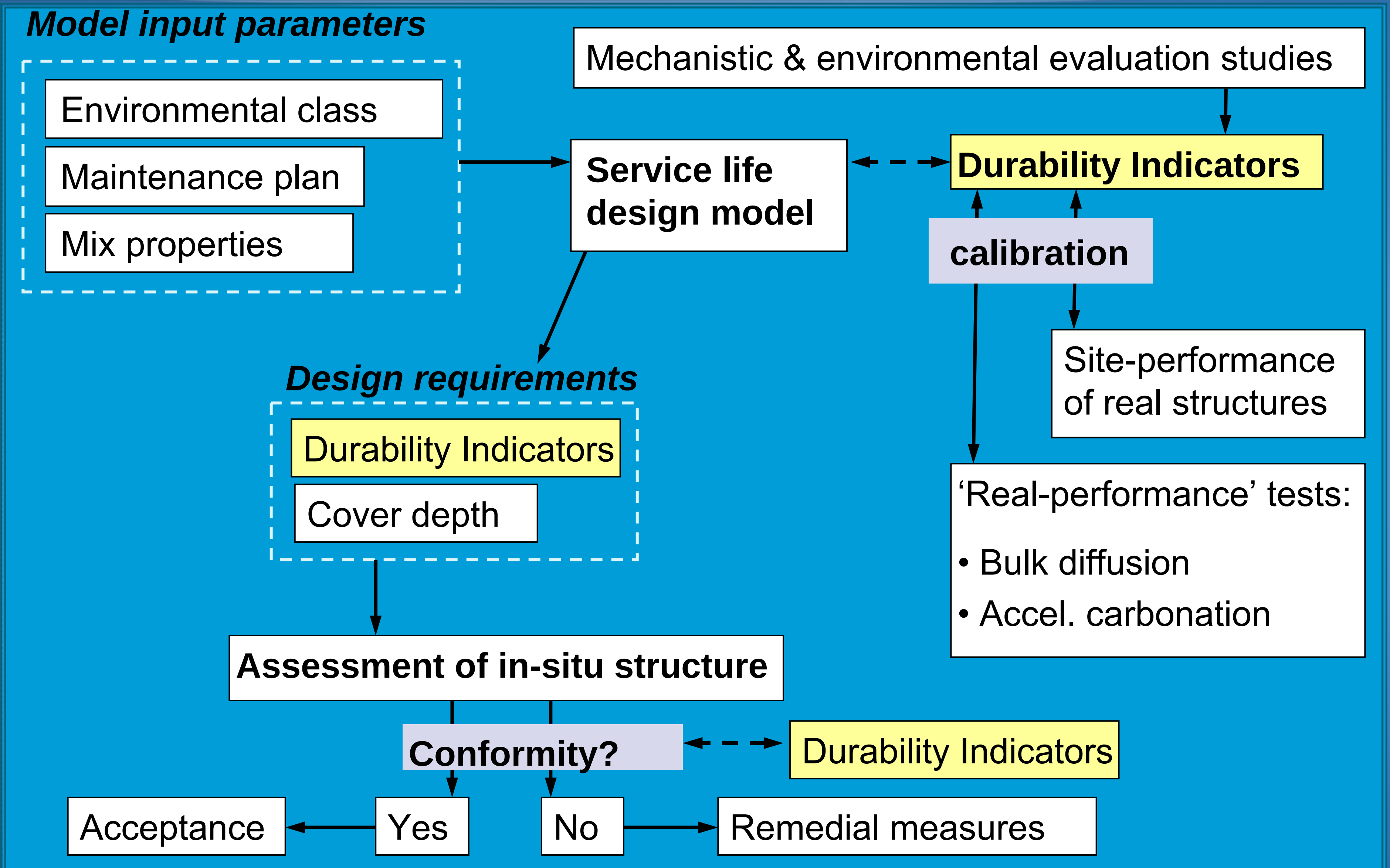
3. Oxygen permeability

Performance-based design

2) Service-life models

- One SLM for chloride resistance, using 28-day chloride conductivity as an input to a Fickian-type model
- One SLM for carbonation resistance, using 28-day OPI as a parameter - empirical
- Initiation models - Account for material type and environment
- Link between DI parameters & use in SLM – integrated approach

Integrated Design Framework & Methodology

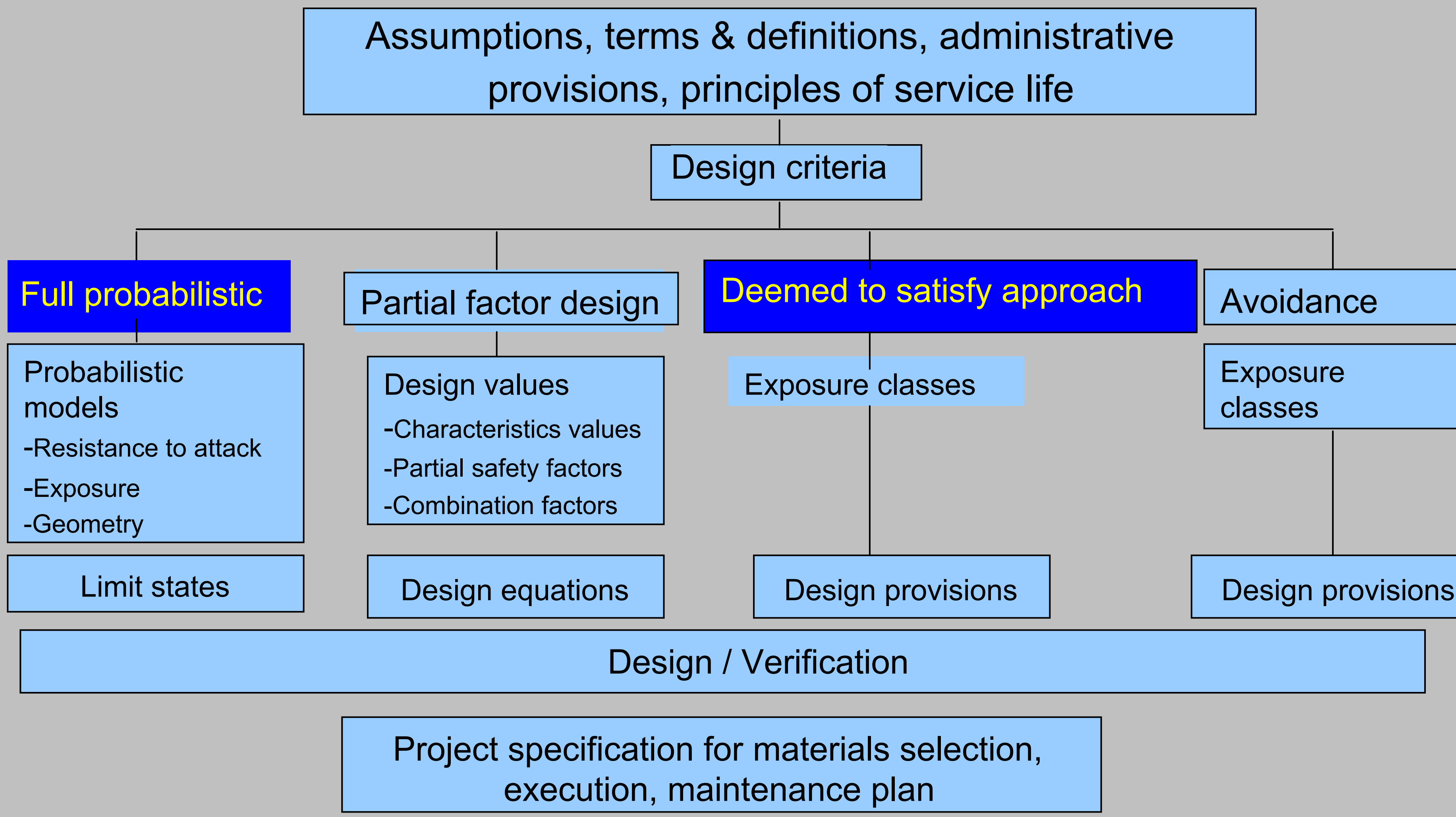


Performance-based design

Design methodology has been applied to two conditions (ref FIB Model Code):

- Deemed-to-satisfy approach
- Full- probabilistic approach

fib Model Code Framework



I) Deemed-to-satisfy approach

1. Performance criteria are drawn from the relevant SLM
2. The emphasis is on as-built concrete quality
3. Characteristic values of design parameters are used
4. Margin allowed between material ‘potential’ and as-built quality

Cont... I) Deemed-to-satisfy approach

1. Performance criteria are drawn from the relevant service-life model

$$C_x = C_s\left(1 - erf\left(\frac{x}{2\sqrt{D_C t}}\right)\right)$$

$$\sigma = \frac{i \cdot t}{V \cdot A}$$

C_x = chloride concentration at depth x and time t

C_s = chloride surface concentration

erf = mathematical error function

D_c = diffusion coefficient

CC values: from < 0.5 to 3.5 mS/cm

Cont... I) Deemed-to-satisfy approach

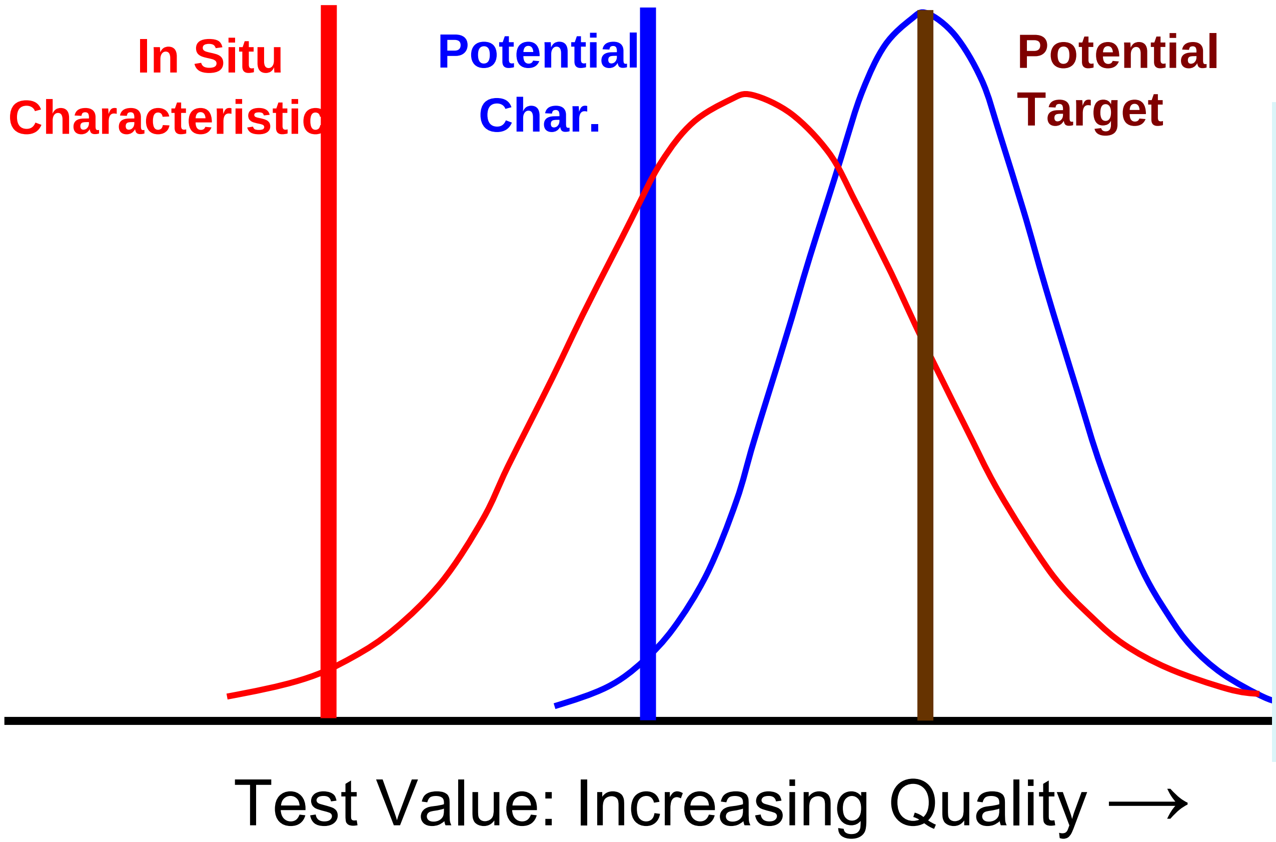
Example of performance criteria – CC values

Table 1: Example: chloride-conductivity, 100 y life

Marine Structure 50-yr design life		Max. chloride conductivity (mS/cm) for various binder types		
Exposure class (based on EN 206)	Cover (mm)	100% CEM I	30% fly ash	50% Corex slag
XS3b: Tidal, splash and wetted spray zones, exposed to abrasion	40	0.45	0.75	1.05
	60	0.95	1.35	1.95
	80	1.30	1.80	2.60

Material Potential vs As-Built Values

2.-4. As-built quality; Char. Values; Margins allowed



These values need to be established by testing of both "laboratory" specimens and samples from the structure.

II) Full-probabilistic Approach

- The methodology for a full-probabilistic design follows limit-state format given in ISO 13823 – which groups the design variables into either load (S) or resistance variables (R)
- Each variable is represented as a stochastic quantity

$$g\left(x, C_{crit}, C_{s}, D_{c}, t, m\right) = R - S = 0$$

II) Full-probabilistic Approach

The design objective is to ensure that the calculated P_f for a given set of parameters does not exceed a target P_f given in the standards for a defined limit state

$$P_f = P\{R - S < 0\} < P_{target}$$

and for the initiation limit state (ILS):

$$P_f = P\{C_{crit} - C_{(x,t)} < 0\} < P_{target,\ ILS}$$

where

$$C_{(x,t)} = C_S\left(1 - \mathrm{erf}\left(\frac{x}{2\sqrt{D_i t^{(1-m)}}}\right)\right)$$

Solution of the LSF is carried out using Monte Carlo Simulation techniques that give the probability of failure

Design Example

Design Example

Concrete piers to be cast in-situ in an extreme splash and tidal marine environment (XS3c) using a cement blend of Portland cement and ground granulated blast furnace slag (GGBS)

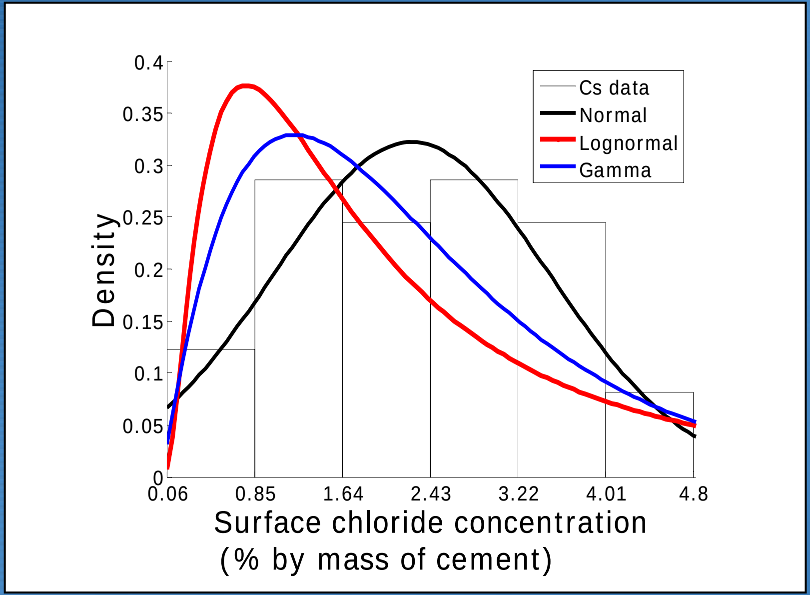
Use a full-probabilistic approach to give a limiting D_i value and corresponding chloride conductivity that should be specified in design

Design life = 100 years

Design Example: Probabilistic approach

Statistical quantification of parameters in the LSF is carried out by fitting distribution curves to data obtained from in-situ testing. e.g. for C_S from profiling tests on existing RC structures (3-75 yrs) in SA

$$g(x, C_{crit}, C_s, D_c, t, m) = R - S = 0$$



Design Example: Probabilistic approach

Using the statistical quantities for each parameter, a MCS of the LSF is done to get an output represented by a cumulative density function (CDF)

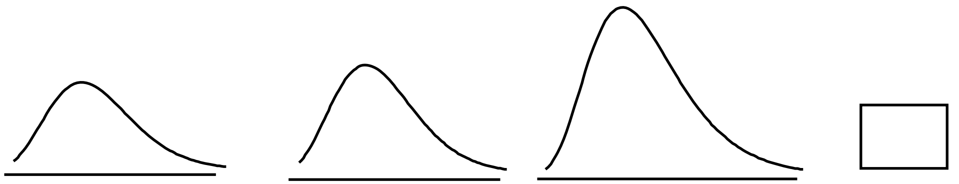
Table 2: Input parameters for reliability analysis of RC Pier

Parameter	*Units*	*Mean*	*COV#*	*Distribution*
x	mm	50	0.2	Normal
C_{crit}	%	0.48	0.31	Normal
C_s	%	4.13	0.21	Gamma
t	years	100	-	Deterministic
m	-	0.68	-	Deterministic

COV# = Coefficient of variation

Design Example: Probabilistic approach

MCS carried out using a Matlab sub-routine



Random values are sampled from each of the defined distributions and LSF condition checked

Process is repeated a number of times

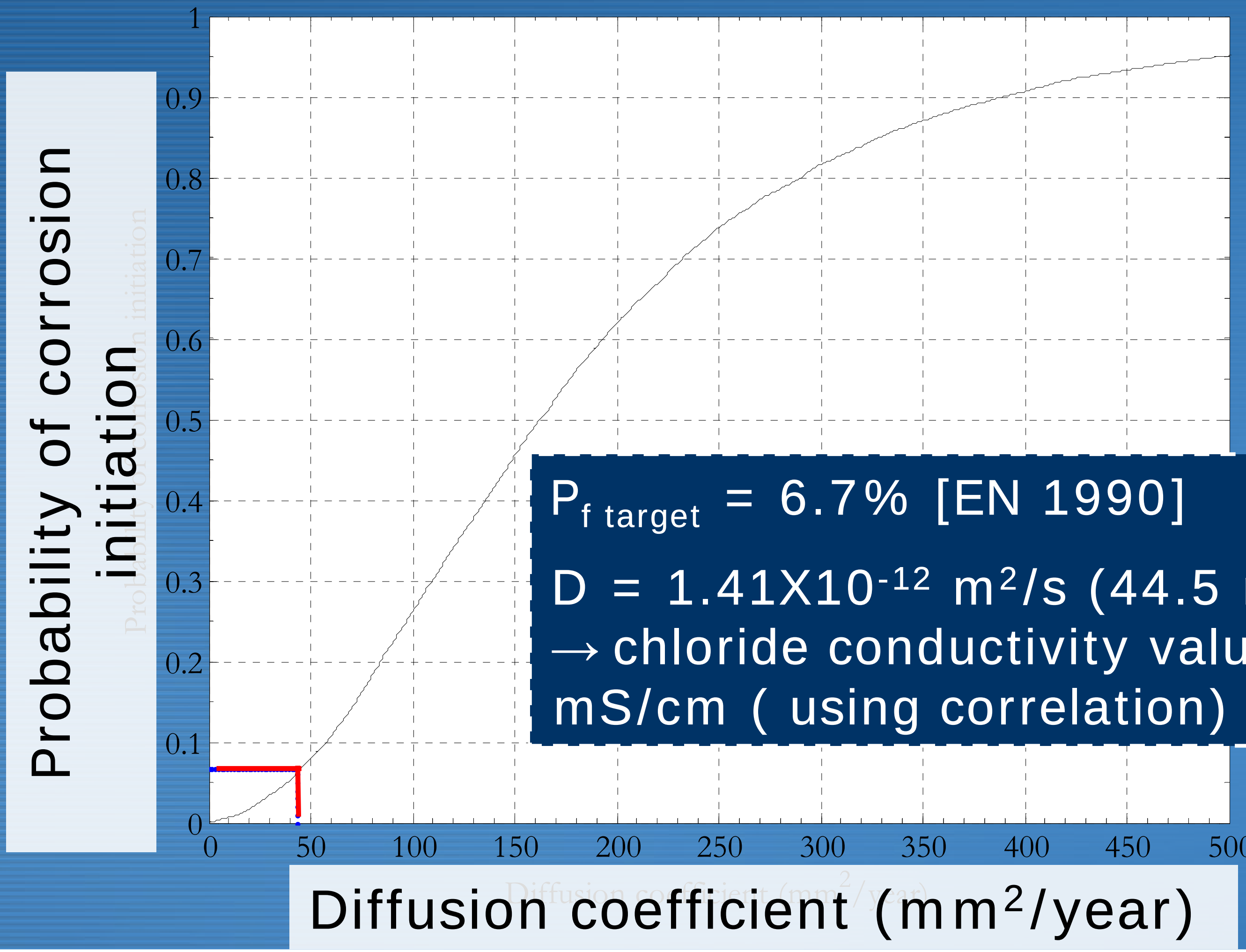
(10 000 iterations =N)

If for a set of random values sampled LHS <0 then failure is said to occur & program registers this event (n)

P_f is then computed as:

$$P_f = \frac{n}{N}$$

Design Example: Probabilistic approach



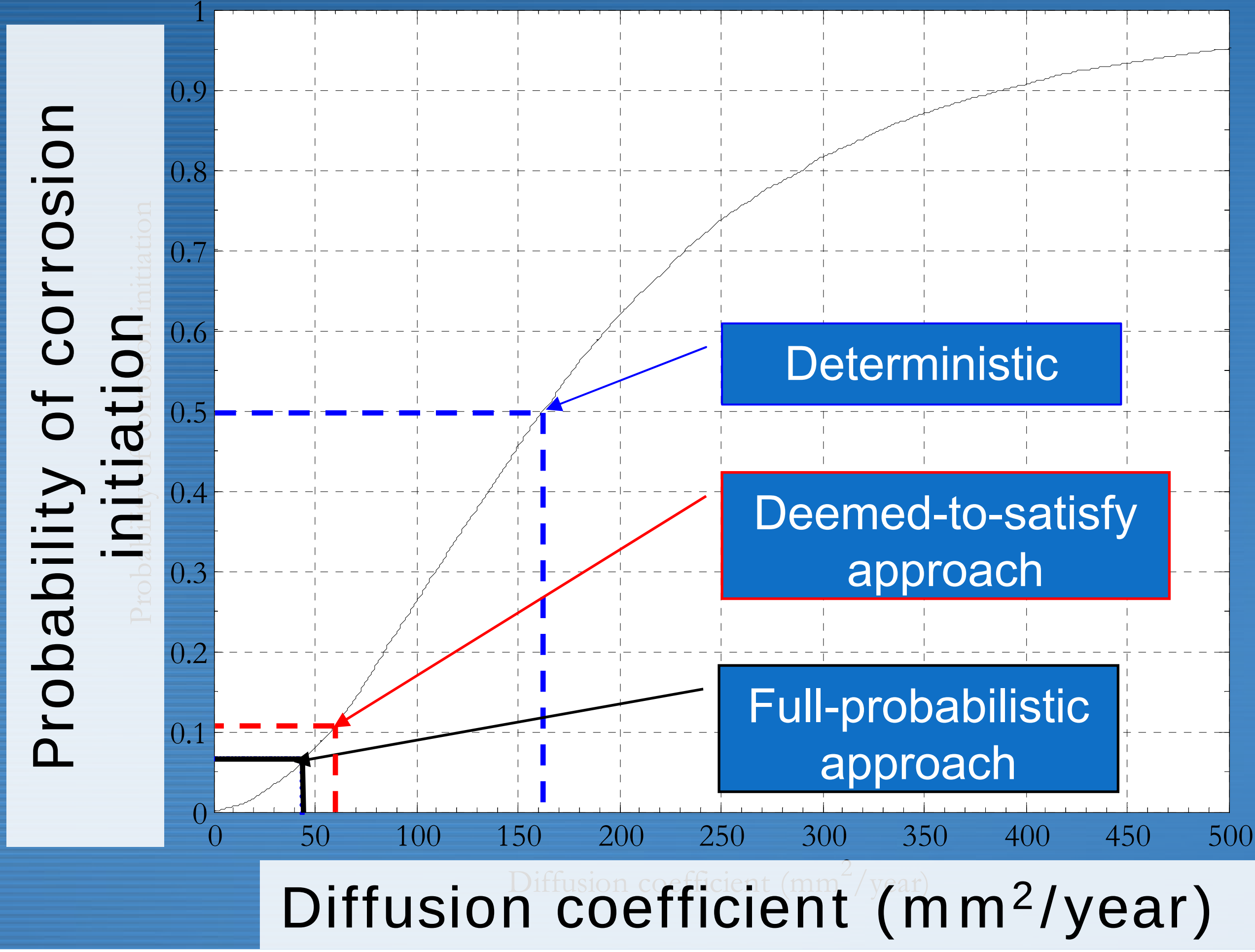
$P_{f\ target}$ = 6.7% [EN 1990]

D = 1.41X10^{-12} m^2/s (44.5 mm^2/year) → chloride conductivity value of 0.9 mS/cm (using correlation)

II) Probabilistic Approach

- The probabilistic approach provides a means to deal with the variability in durability design parameters
- The approach gives a more realistic representative of the 'real life' situation where variability is inherent, as compared to the deemed to satisfy or deterministic models

Deemed-to-satisfy vs Full Probabilistic



Performance-based approach

It can be argued that a purely deterministic approach should give a CC equivalent to 50% P_f

Table 3: Design specifications (XS3b; Cover = 50mm ± Δx_{dev}; CEM III A)

Design method	*Chloride conductivity value*
Deterministic (50% P_f)	1.92 mS/cm
Deemed-to-satisfy (DTS)	1.05 mS/cm
Full-probabilistic (6.7% P_f)	0.9 mS/cm

Performance-based approach vs Prescriptive Approach

For the example, the table below compares three approaches to durability design

Table 4: Design specifications (XS3b; Cover = 50mm ± Δx_{dev}; CEM III A)

Design method	*Quality control test value e.g. CC (CEM IIIA)*	*water/ binder*	
		CEM IIIA	*CEM I (Equiv.)*
Prescriptive approach (EN 1992-1-1:2004)	-	0.4	-
Deemed-to-satisfy	1.05 mS/cm	0.75#/0.55	0.30
Full-probabilistic	0.9 mS/cm	0.70#/0.55	0.25

= due to limitations in the current state of knowledge, a maximum w/b=0.55 is recommended

Summary of Performance-based approach:

- Quantification of the problem,
- Idea of design ‘targets’, and
- A design framework for engineers

Links between sustainability and durability

Links between sustainability and durability

Durability design and Sustainability:

- ❑ Inadequate durability leads to need for repair and rehabilitation - unnecessary waste of resources
- ❑ Should allow efficient use of resources
- ❑ Should allow utilization of new materials

BUT: how can we use the concepts of durability design to assist us to develop 'sustainability design'

Links between sustainability and durability

- So far structural reliability theory has provided a *quantitative link* between the practice of structural engineering and its economic and societal consequences – mainly struc. safety

Table 5: Consequences classes for SLS (FIB Model Code)

*Consequences class**	*Reliability level*	*Probability of failure (P_{target})*
CC1 (Low)	1.0	16%
CC2 (Normal)	1.5	6.7%
CC3 (High)	2.0	2.3%

*The reliability level is selected based on consequences of failure i.e. If there will be many lives lost (public building) then a higher reliability level is selected

Links between sustainability and durability

- The target prob. of failure (P_{target}) values are derived from optimizing the direct economic benefits/costs incurred by the owner/manager of the infrastructure.
- If the calculated P_f departs from P_{target} then the design is deemed uneconomical
- The P_{target} values at this stage relate to design standards established by developed countries; these may not relate to economic conditions faced in developing countries, e.g.
  - ❑ quality control levels might have to differ
  - ❑ 'development' may be more important than resource minimisation

Links between sustainability and durability

- At present, the P_{target} value does not assign a value to the loss suffered by the society (user) when durability/structural failure occurs E.g. loss due to:
  - Inconvenience during repair
  - Loss of assets in case of structural failure
  - Loss of income due to repair
  - Possible loss of life

Links between sustainability and durability

- Likewise, the environmental consequences are equally important but so far have not been included in the analysis of P_{target} (or an equivalent formulation)
- Environmental consequences of durability failure may include:
  - Consumption of additional energy and resources due to repair
  - Generation of wastes during repair
  - Loss of the original materials

Links between sustainability and durability

- We need to go a step further and estimate (using actual values) the societal and environmental consequences i.e. the explicit impact of durability/structural failure related to a particular target reliability
- These might vary from country to country depending on the state of development

Links between sustainability and durability

Previous cost minimization function:

$$Z(p) = C(p) + \left\lfloor F \times P_f \right\rfloor$$

P = design criteria
C(p) = Design and construction cost
F = Direct material losses due to failure

Proposed cost minimization function:

$$Z(p) = C(p) + \left\lfloor (F + S + E) \times P_f \right\rfloor$$

S = Societal cost due to failure
E = Environmental cost

Concluding comments

- To summarise: we have argued that considerations of sustainability should relate to concepts embedded in service life and performance-based design requirements of structures
- This would in turn allow for the comparison of different material design options on the basis of their performance, as opposed to the current practice of comparing their costs and/or environmental impacts without a common reference of performance
- Introduction of such a system will lead to the promotion of new environmentally friendly structures that meet economic and societal needs

Thank You