


SHRP2 SOLUTIONS
STRATEGIC HIGHWAY RESEARCH PROGRAM

Introduction to Service Life Design

Virginia DOT Workshop – Charlottesville, VA

Mike Bartholomew, P.E.
Regional Discipline Lead, North American Bridges
CH2M

October 4, 2017

U.S. Department of Transportation
Federal Highway Administration

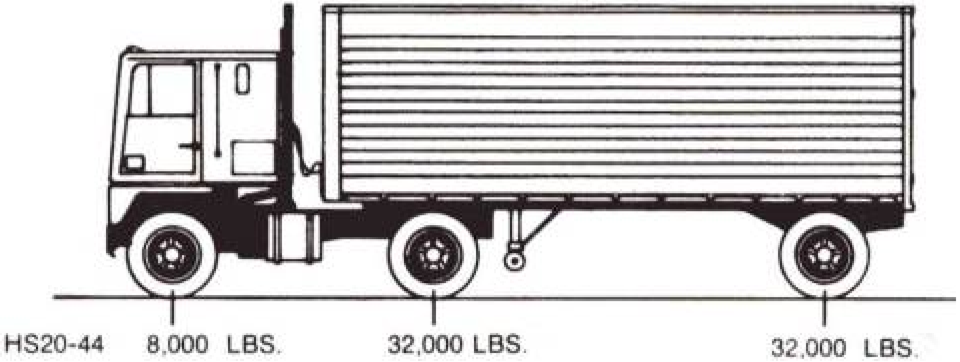
American Association of State Highway and Transportation Officials
AASHTO

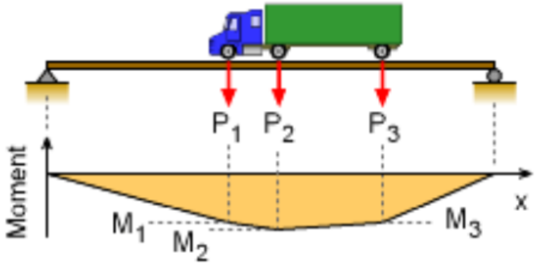
Presentation Overview

- Service Life Design Background
- Deterioration based on Environmental Exposure
- Deterioration Modeling
- Service Life Design Strategies
- Current Code Requirements
- Summary

Service Life Background

- Bridge design focuses on structural engineering
  - Determining loads, sizing components, and selecting materials by their strength properties (f'c, fy, etc.)





Typical Moment Diagram for a Series of Point Loads

  - Extremely important, but does little to ensure that a structure will remain in use for a given period of time

Service Life Background

- When a structure reaches the end of its life, the cause is either functional obsolescence, or
  - The result of material deterioration

  - Due to the environmental exposure conditions

Service Life Design Principles

- All materials deteriorate with time
- Every material deteriorates at a unique rate
- Deterioration rate is dependent on:
  - Environmental exposure conditions
  - Material's protective systems – durability properties

Service Life Design (SLD)

- Design approach to resist deterioration caused by environmental actions
  - Also called Durability Design
  - Often referred to as Design for 100-year Service Life

- <u>Not</u> designing for the Service Limit States I, II, and III per LRFD 3.4

Service Life Design (SLD)

- Similar to strength design to resist structural failure caused by external loads
  - External Loads ← → Environmental Actions
  - Material Strength ← → Durability Properties
- Both strength and Service Life Designs satisfy scientifically based modeling equations

Goals of Service Life Design

- **Owners** – Need assurance that a long-lasting structure will be designed, built, and operated (Effective use of public funding $$)

- **Engineers/Contractors/Asset Managers** – Need quantifiable scientific methods to evaluate estimated length of service for bridge components and materials

Service Life Background

- Significant research has been completed over the past 25 years on how materials deteriorate with time (particularly reinforced concrete)
- Mathematical solutions have been developed to model deterioration behavior

Past Practice – 1996-2000

ACI 365.1R-00

Service-Life Prediction—State-of-the-Art Report

Reported by ACI Committee 365

James R. Clifton*† Chairman

Dan J. Naus*‡ Secretary

S. L. Amey*
J. P. Archibald
N. R. Buenfeld
P. D. Cady*
C. W. Dolan
M. Geiker
C. J. Hookham
W. J. Irwin
A. Kehnemui
D. G. Manning
P. K. Mukherjee
J. Pommersheim
M. D. Thomas
R. E. Weyers*

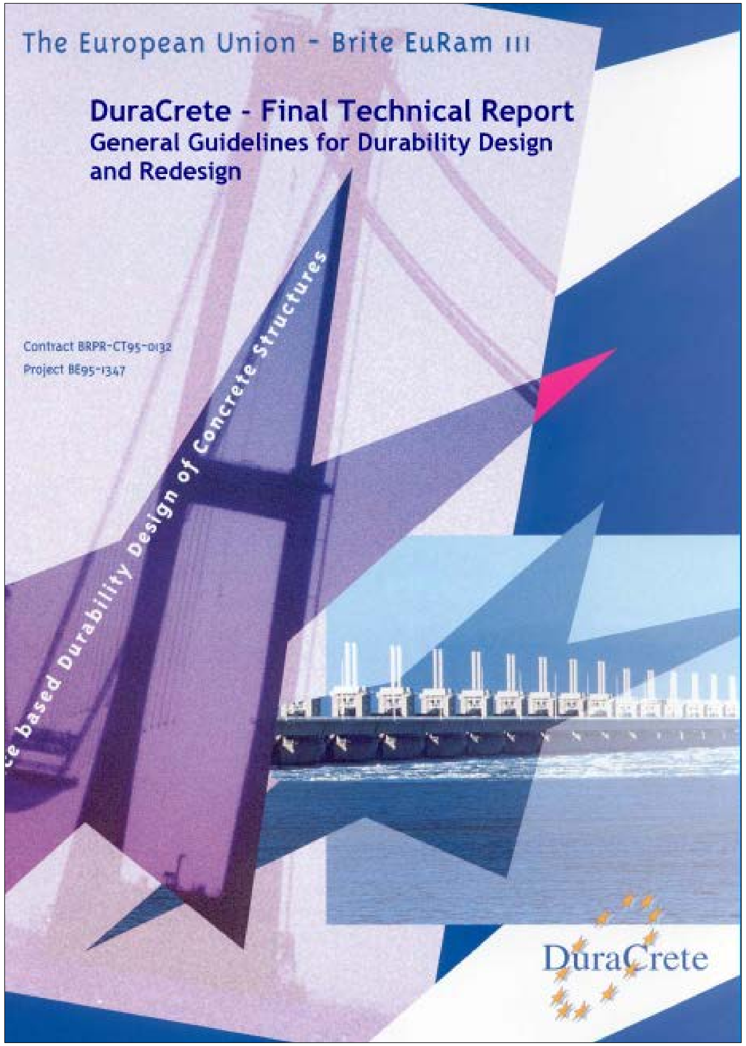
*Report chapter coordinators
†Deceased
‡Report coordinator

This report presents current information on the service-life prediction of new and existing concrete structures. This information is important to both the owner and the design professional. Important factors controlling the service life of concrete and methodologies for evaluating the condition of the existing concrete structures, including definitions of key physical properties, are also presented. Techniques for predicting the service life of concrete and the relationship between economics and the service life of structures are discussed. The examples provided discuss which service-life techniques are applied to concrete structures or structural components. Finally, needed developments are identified.

Keywords: construction; corrosion; design; durability; rehabilitation; repair; service life.

CONTENTS

ACI 365.1R-00 became effective January 10, 2000.



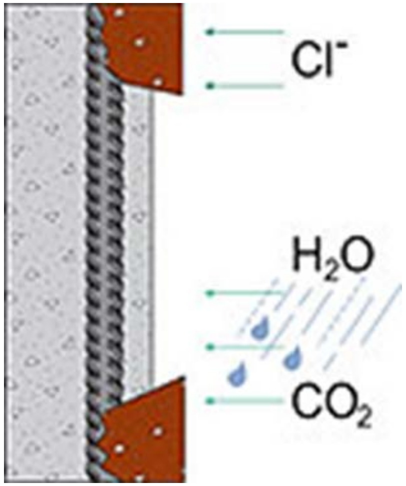
Common Deterioration Types

- Reinforcing steel corrosion
- Concrete cracking, spalling, delamination

- Structural steel corrosion following breakdown of protective coating systems

Environmental Exposure

- Chlorides from sea water or de-icing chemicals
- CO_2 from many wet / dry Cycles
- Temperature / Relative Humidity
- Freeze / Thaw Cycles
- Abrasion (ice action on piers, studded tires on decks)



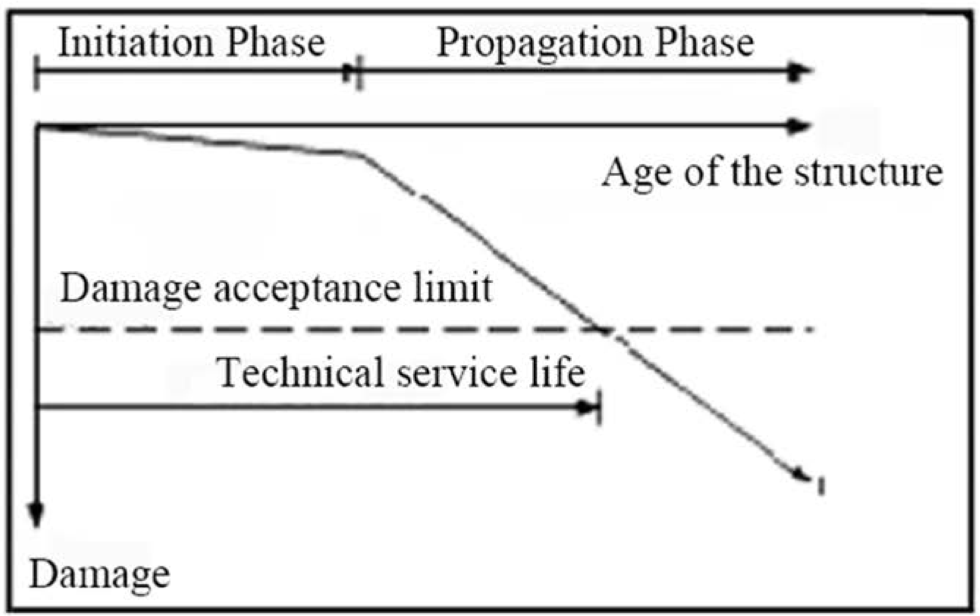
Material Resistance

- Reinforced Concrete
  - Adequate reinforcing steel cover dimension
  - High-quality concrete in the cover layer

- Structural Steel
  - Chemical composition for corrosion resistance
  - Protective coatings

Deterioration Modeling

- Reinforcing Steel Corrosion is defined with a two-phase deterioration model
  - Initiation – No visible damage is observed
  - Propagation – Corrosion begins and progresses



Service life of concrete structures. A two-phase modelling of deterioration.
[Tuutti model (1982)]

Example Deterioration Model

- Chloride Ingress – Fick's 2nd Law of Diffusion for Corrosion Initiation

$$C_{crit} \geq C(x = a, t) = \mathbf{C_o} + (\mathbf{C_{s,\Delta x}} - \mathbf{C_o}) \cdot \left[1 - \operatorname{erf}\left(\frac{\mathbf{a} - \Delta x}{2\sqrt{D_{app,C} \cdot t}}\right)\right]$$

$$D_{app,C} = k_e \cdot \mathbf{D_{RCM,0}} \cdot k_t \cdot A(t)$$

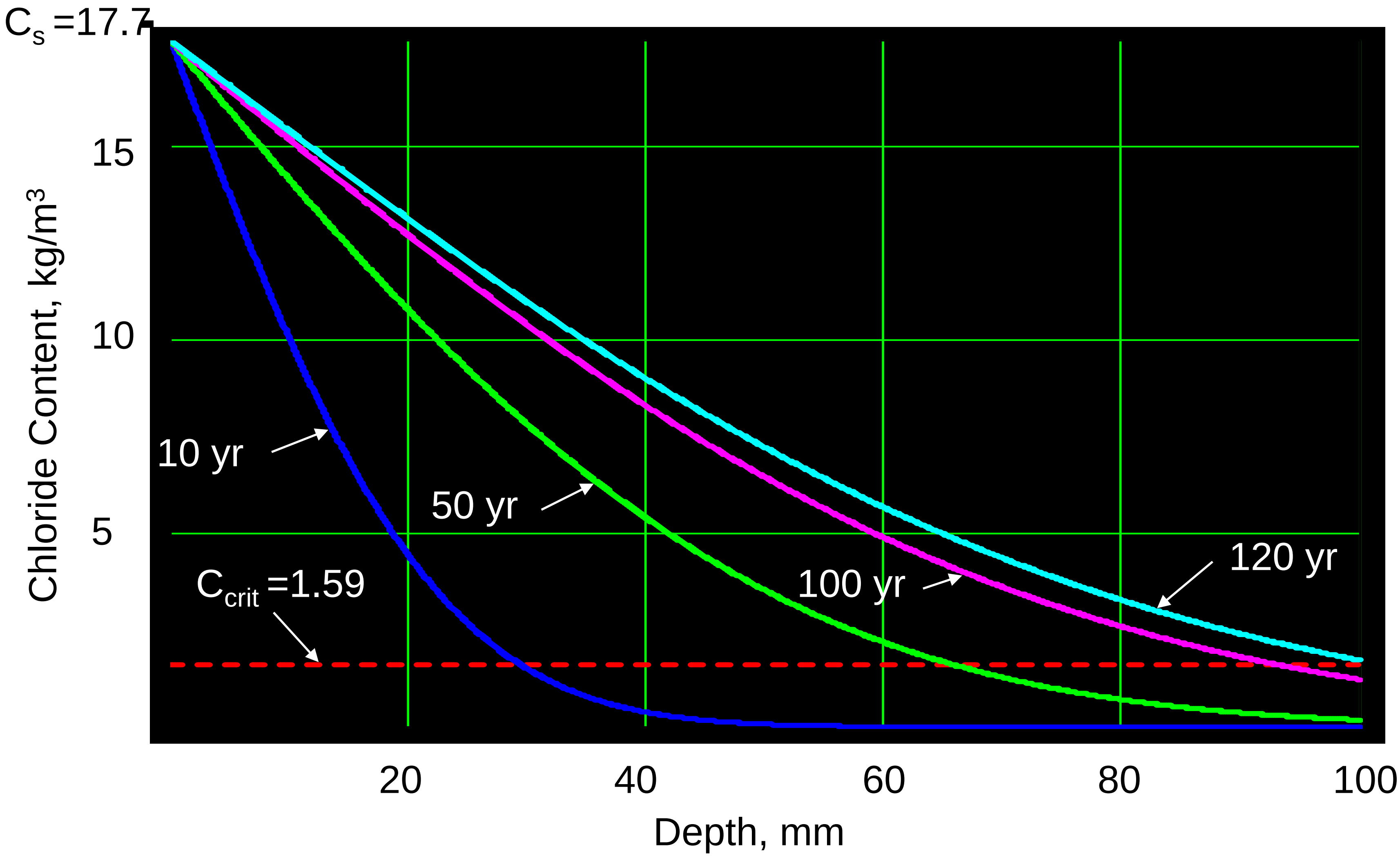
$$k_e = \exp\left(b_e\left(\frac{1}{T_{ref}} + \frac{1}{\mathbf{T_{real}}}\right)\right)$$

$$A(t) = \left(\frac{t_o}{t}\right)^{\boldsymbol{\alpha}}$$

- **Red – Environmental Loading**
  - C_o & C_s are the Chloride Background and Surface Concentrations
  - T_{real} is the Annual Mean Temperature at the project site
- **Green – Material Resistance**
  - $D_{RCM,0}$ is the Chloride Migration Coefficient, α is the Aging Exponent, both are functions of the concrete mix (*W/C* ratio, SCMs)
  - a is the Concrete Cover

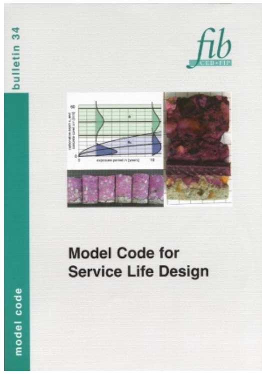
Chloride Profiles vs. Age

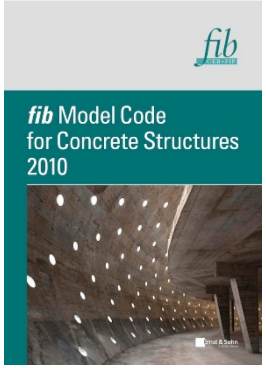
constant $D_{app,c}$ = 15.1 mm^2/yr



Current Specifications

- *fib* Bulletin 34 – Model Code for Service Life Design (2006)
- *fib* Model Code for Concrete Structures 2010
- ISO 16204 – Durability – Service Life Design of Concrete Structures (2012)
- All focus on concrete structures only, little available for steel






INTERNATIONAL STANDARD

ISO 16204

First edition
2012-09-01

Durability — Service life design of concrete structures

Durabilité — Conception de la durée de vie des structures en béton

Service Life Design Strategies

- Avoidance of deterioration – Strategy A

- Design based on deterioration from the environment – Strategy B
  - Full probabilistic design
  - Deemed to satisfy provisions
  - Semi-probabilistic, partial factor, or deterministic

- “One size does not fit all” – Multiple strategies may be used on a single bridge

Avoidance of Deterioration

- Also called the “Design-Out” approach
- Achieved by either:
  - Eliminating the environmental exposure actions
    - e.g., Use of alkali-non-reactive aggregates
  - Providing materials with resistance well beyond the requirements needed
    - e.g., Use of stainless steel reinforcement
    - Not always the most cost-effective solution

Full Probabilistic Design

- Uses mathematical models to describe observed physical deterioration behavior
- Model variables are:
  - Environmental exposure actions (demands)
  - Material resistances (capacities)
- Variables represented by mean values and distribution functions (std. deviations, etc.)
- Probabilistic, Monte-Carlo type analysis to compute level of reliability

Full Probabilistic Design

- Reliability based like that used to develop AASHTO LRFD code for structural design
- Sophisticated analysis often considered beyond the expertise of most practicing bridge engineers
- Work effort may be regarded as too time consuming for standard structures
- Has been reserved for use on large projects

Deemed to Satisfy Method

- Prescriptive approach used in most major design codes, like AASHTO LRFD sections 2.5.2.1 & 5.12
- Based on some level of past performance – “Rules of Thumb”
- No mathematical deterioration modeling
- Simplistic and not quantifiable
- Lowest level of reliability

AASHTO LRFD Provisions

- 2.5.2.1 – Durability
  - Contract documents shall call for quality materials and … high standards of fabrication and erection.
  - Structural steel shall be self-protecting, or have long-life coating systems or cathodic protection.
- Good intention, but hardly quantifiable

AASHTO LRFD Provisions

- 5.12.1 – Durability – General
  - Concrete structures shall be designed to provide protection of the reinforcing and prestressing steel against corrosion throughout the life of the structure.
  - Special requirements that may be needed to provide durability shall be indicated in the contract documents.
- Again, not very much guidance

AASHTO LRFD Provisions

- 5.12.3 – Durability – Concrete Cover
  - Cover for unprotected prestressing and reinforcing steel shall not be less than that specified in Table 5.12.3-1 and modified for *W/C* ratio…
  - Modification factors for *W/C* ratio shall be the following:
    - For W/C $\leq$ 0.4 ……………………………………….. 0.8
    - For W/C $\geq$ 0.5 ……………………………………….. 1.2

AASHTO LRFD Provisions

- Specified concrete cover dimensions

SECTION 5: CONCRETE STRUCTURES

Table 5.12.3-1—Cover for Unprotected Main Reinforcing Steel (in.)

Situation	Cover (in.)
Direct exposure to salt water	4.0
Cast against earth	3.0
Coastal	3.0
Exposure to deicing salts	2.5
Deck surfaces subject to tire stud or chain wear	2.5
Exterior other than above	2.0

- Cover minimally related to concrete properties

ACI-318 Durability Provisions

TABLE 4.2.1 — EXPOSURE CATEGORIES AND CLASSES

Category	Severity	Class	Condition	
F Freezing and thawing	Not applicable	F0	Concrete not exposed to freezing-and-thawing cycles	
	Moderate	F1	Concrete exposed to freezing-and-thawing cycles and occasional exposure to moisture	
	Severe	F2	Concrete exposed to freezing-and-thawing cycles and in continuous contact with moisture	
	Very severe	F3	Concrete exposed to freezing-and-thawing and in continuous contact with moisture and exposed to deicing chemicals	
			Water-soluble sulfate (SO_4) in	Dissolved sulfate (SO_4)
permeability	Required		permeability is required.	
C Corrosion protection of reinforcement	Not applicable	C0	Concrete dry or protected from moisture	
	Moderate	C1	Concrete exposed to moisture but not to external sources of chlorides	
	Severe	C2	Concrete exposed to moisture and an external source of chlorides from deicing chemicals, salt, brackish water, seawater, or spray from these sources	

*Percent sulfate by mass in soil shall be determined by ASTM C1580.
†Concentration of dissolved sulfates in water in ppm shall be determined by ASTM D516 or ASTM D4130.

TABLE 4.3.1 — REQUIREMENTS FOR CONCRETE BY EXPOSURE CLASS

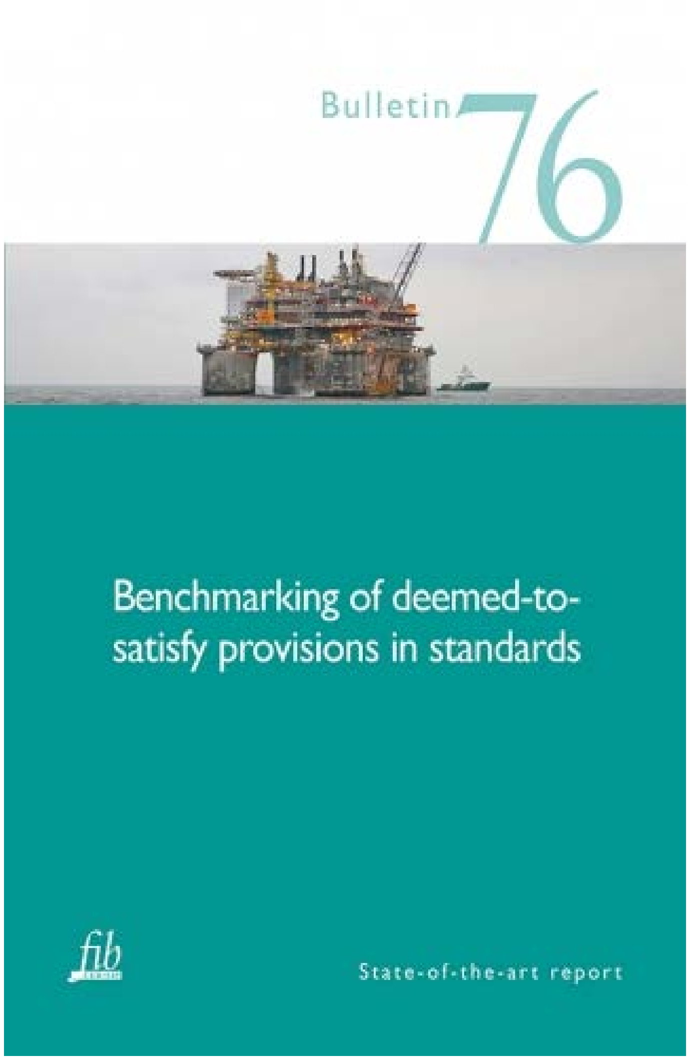
Exposure Class	Max. *w/cm**	Min. f'_c, psi	Additional minimum requirements	
			Air content	Limits on cementitious materials
F0	N/A	2500	N/A	N/A
F1	0.45	4500	Table 4.4.1	N/A
F2	0.45	4500	Table 4.4.1	N/A

Exposure Class	Max. *w/cm**	Min. f'_c, psi	Maximum water-soluble chloride ion (Cl^-) content in concrete, percent by weight of cement# — Reinforced concrete	Maximum water-soluble chloride ion (Cl^-) content in concrete, percent by weight of cement# — Prestressed concrete	Related provisions
C0	N/A	2500	1.00	0.06	None
C1	N/A	2500	0.30	0.06	None
C2	0.40	5000	0.15	0.06	7.7.6, 18.16**

*For lightweight concrete, see 4.1.2.
†Alternative combinations of cementitious materials of those listed in Table 4.3.1 shall be permitted when tested for sulfate resistance and meeting the criteria in 4.5.1.
‡For seawater exposure, other types of portland cements with tricalcium aluminate (C_3A) contents up to 10 percent are permitted if the *w/cm* does not exceed 0.40.

Deemed to Satisfy Evaluation

- *fib* Commission 8 – Durability
  - Used full probabilistic methods to evaluate level of reliability for deemed to satisfy code provisions for chloride ingress
  - 9 countries evaluated, including US
  - Results published in 2015



Reliability Levels

Summary of Reliability Index, β versus Probability of Failure, P_f			
P_f	Reliability	$\beta = -\phi_U^{-1}(P_f)$	where $-\phi_U^{-1}(P_f)$ is defined as the inverse standard normalized distribution function
			Example
10%	90%	1.3	fib Bulletin 34 Model Code for Service Life, corrosion initiation
6.7%	93.3%	1.5	Eurocode EN 1990 (service limit state calibrated for a 50 year design life)
1.0%	99%	2.3	
0.1%	99.9%	3.1	
0.02%	99.98%	3.5	AASHTO LRFD Strength I (calibrated for 75 year design life)
0.0072%	99.9928%	3.8	Eurocode EN 1990 (ultimate limit state calibrated for a 50 year design life)
50%	50%	0.0	Flipping a coin
80%	20%	-0.8	fib TG8.6 Deemed to Satisfy for exposure XD3 (chlorides other than seawater) in USA - 50 year design life

Semi-Probabilistic Design

- Uses same mathematical model as Full Probabilistic Design
- Load factors on environmental demands
- Resistance factors on material properties
- Direct solution to model equations
- Not enough data to properly determine appropriate factors and reliability level
- Method expected to be adopted by codes in the future

Service Life Designed Structures

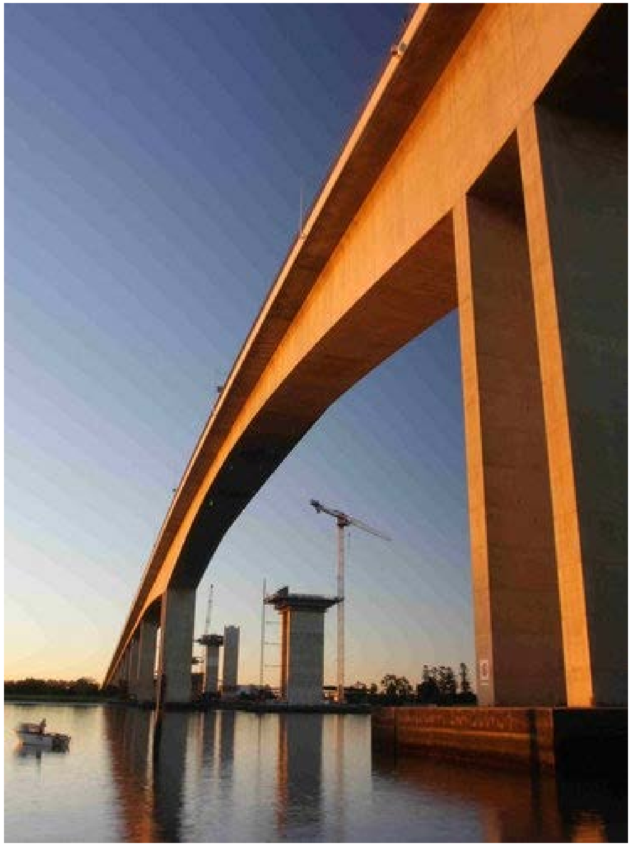
- Confederation Bridge, Canada –1997 (100 years)

Service Life Designed Structures

- Great Belt Bridge, Denmark – 1998 (100 years)

Service Life Designed Structures

- Gateway Bridge, Brisbane – 2010 (300 years)



Development of SHRP2 R19A

- Service Life Design is relatively new and unfamiliar to the US Bridge Community
- FHWA, AASHTO & TRB initiated project R19A through the 2nd Strategic Highway Research Program (SHRP2)
  - Bridges for Service Life Beyond 100 Years: Innovative Systems, Subsystems and Components
- Awarded projects to 7 agencies to develop practical concepts for implementing SLD

Summary

- Durability or Service Life Design is:
  - A design approach to resist deterioration caused by environmental actions
- Design Guides/Codes are available:
  - fib Bulletin 34 – Model Code for Service Life Design
- Four Different Levels of Service Life Design Strategies can be utilized on a single bridge
  - Avoidance, Deemed to Satisfy, Full-Probabilistic & Semi-Probabilistic
- SHRP2 R19A developed to further research and implementation of SLD

Questions?

Implementation Leads:

- Patricia Bush, *AASHTO Program Manager for Engineering,* pbush@aashto.org
- Raj Ailaney, *FHWA Senior Bridge Engineer,* Raj.Ailaney@dot.gov

Subject Matter Expert Team:

- Mike Bartholomew, *CH2M,* mike.bartholomew@ch2m.com
- Anne-Marie Langlois, *COWI North America,* amln@cowi.com

Resource: AASHTO's R19A Product Page

- http://shrp2.transportation.org/Pages/ServiceLifeDesignforBridges.aspx