



SHRP2 SOLUTIONS
STRATEGIC HIGHWAY RESEARCH PROGRAM

Durability Design & Structure Birth Certificate
SHRP2 Service Life Design for Bridges (R19-A)

Implementation Plan Webinar

February 2, 2015

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U.S. Department of Transportation
Federal Highway Administration

American Association of State Highway and Transportation Officials
AASHTO

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

Agenda

- Introduction
- Service Life Design Principles
- Durability Assessment Guides/Tools
- Service Life Design Strategies
- Through Life Management
- Structure Birth (or Durability) Certificate
- Existing Structures
- Summary Review

Introduction

- Service Life Design History
  - EU Brite/EuRam III Project: Duracrete
    - Probabilistic Performance-based Durability Design of Concrete Structures, 1996-2000 (started in 80's)
  - European Community Competitive and Sustainable Growth Program – LIFECON
    - Life Cycle Management of Concrete Infrastructures for Improved Sustainability, 2001-2003
  - International Federation for Structural Concrete (*fib*)
    - Model Code for Service Life Design, 2006

Introduction

- Service Life Design first introduced in the US to ASBI at the 2005 Convention in Washington, DC
  - "*Design and Construction of Segmental Concrete Bridges for Service Life of 100 to 150 Years*", by Steen Rostam / COWI, Denmark

My Interest in Service Life Design

- Unable to Respond Adequately to:
  - Questions from Owners:
    - “We are designing bridges to last 75+ years now, aren’t we?”
    - “Can you design a repair to make the bridge last 10-15 more years?”
  - Requirements in Requests for Proposals:
    - Design the bridge for 100 year life span.
    - Explain how you will achieve the design service life of the bridge
- Became Involved in *fib* Commission 5

Service Life Misconceptions

- Bridges designed to AASHTO LRFD have an expected service life of 75 years
  - LRFD Section 1.2 – Definitions
    - Design Life – Period of time on which the statistical derivation of transient loads is based – 75 years for these Specifications.
    - Service Life – The period of time that the bridge is expected to be in operation.

Service Life Misconceptions

- It's become popular to state that a new bridge has been designed for a Service Life of 75, 100, 125 years (or more)

... whether or not a true Service Life Design has been undertaken

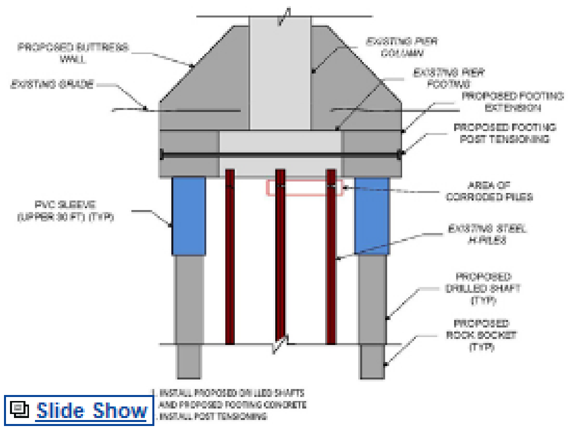
ENR.com
Engineering News-Record

Issue: 09/29/2014

WisDOT Orders Further Investigations for Repaired Leo Frigo Bridge Piers

09/29/2014

By Candy McCampbell



Courtesy WisDOT

Repairs to date include rock sockets at base of five pile foundations

Inspection of the Leo Frigo Bridge in Green Bay, Wis., that developed a 2.5-ft sag last year after a piling buckled also showed severe corrosion in four other piers that "significantly reduced the structural capacity" of their foundation systems, a state report said.

Pier 22, along with Piers 21-25, were classified as "Tier 1" in terms of damage severity and potential for safety problems, and had to be repaired before the bridge could be used. The repairs were completed and the bridge re-opened in January, though the studies and analysis continued. An executive summary of the report was issued Aug. 27 and the full report is due late this year.

The Tier 1 piers got a new drilled shaft foundation, with 5-ft-dia drilled shafts approximately 120 ft deep with a 4.5-ft diameter rock socket keyed 7.5 ft into bedrock, says Tom Buchholz, Wisconsin Dept. of Transportation project manager for the bridge repairs.

The new foundations can support the entire pier design load and should last for 75 years, the report said.

The new foundations … should last for 75 years

Service Life Design Principles

- All Materials Deteriorate with Time
- Every Material Deteriorates at a Unique Rate
- Deterioration Rate is Dependent on
  - The Environmental Exposure Conditions
  - The Material’s Protective Systems

Environmental Exposure

Exposure Classes – European Standard EN-206-1

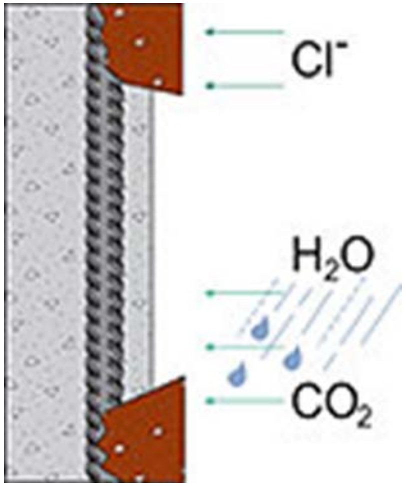
Class/Level	Description
X0	No Risk of Corrosion or Attack
XC1-XC4	Corrosion Induced by Carbonation
XD1-XD3	Corrosion induced by chlorides other than from sea water
XS1-XS3	Corrosion induced by chlorides from sea water
XF1-XF4	Freeze/thaw attack with or without de-icing agents
XA1-XA3	Chemical attack

Material Resistance

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

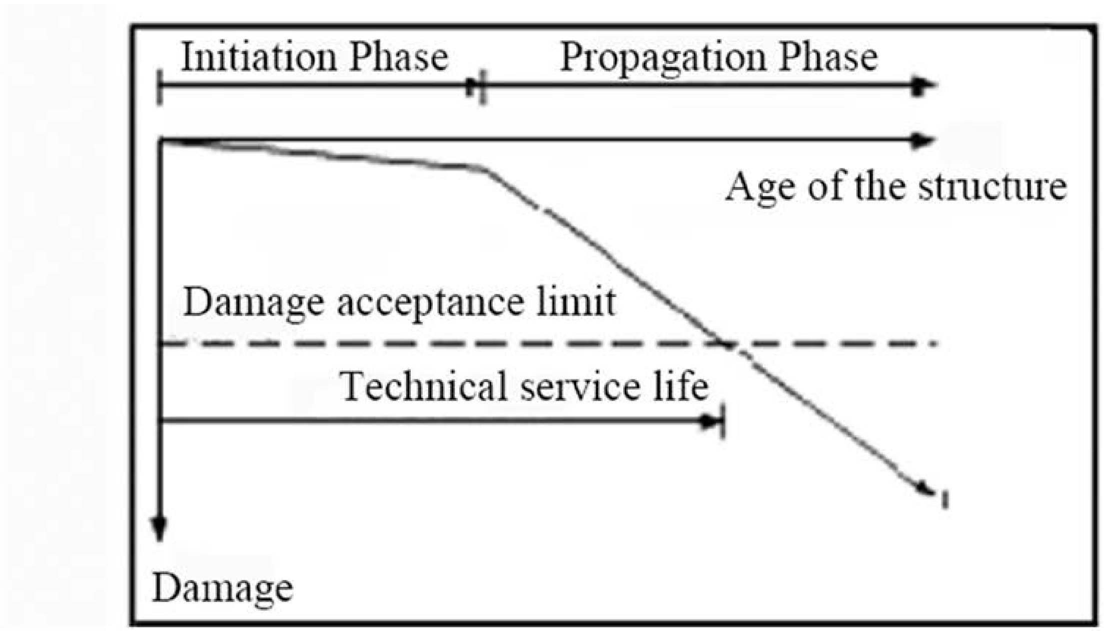
Service Life Design Principles

- Material Deterioration Mechanisms
  - Reinforcing Steel Corrosion due to:
    - Chloride Ingress
    - Carbonation
  - Concrete Deterioration due to:
    - Freeze-Thaw
    - Abrasion
    - Alkali-Silica Reaction (ASR)



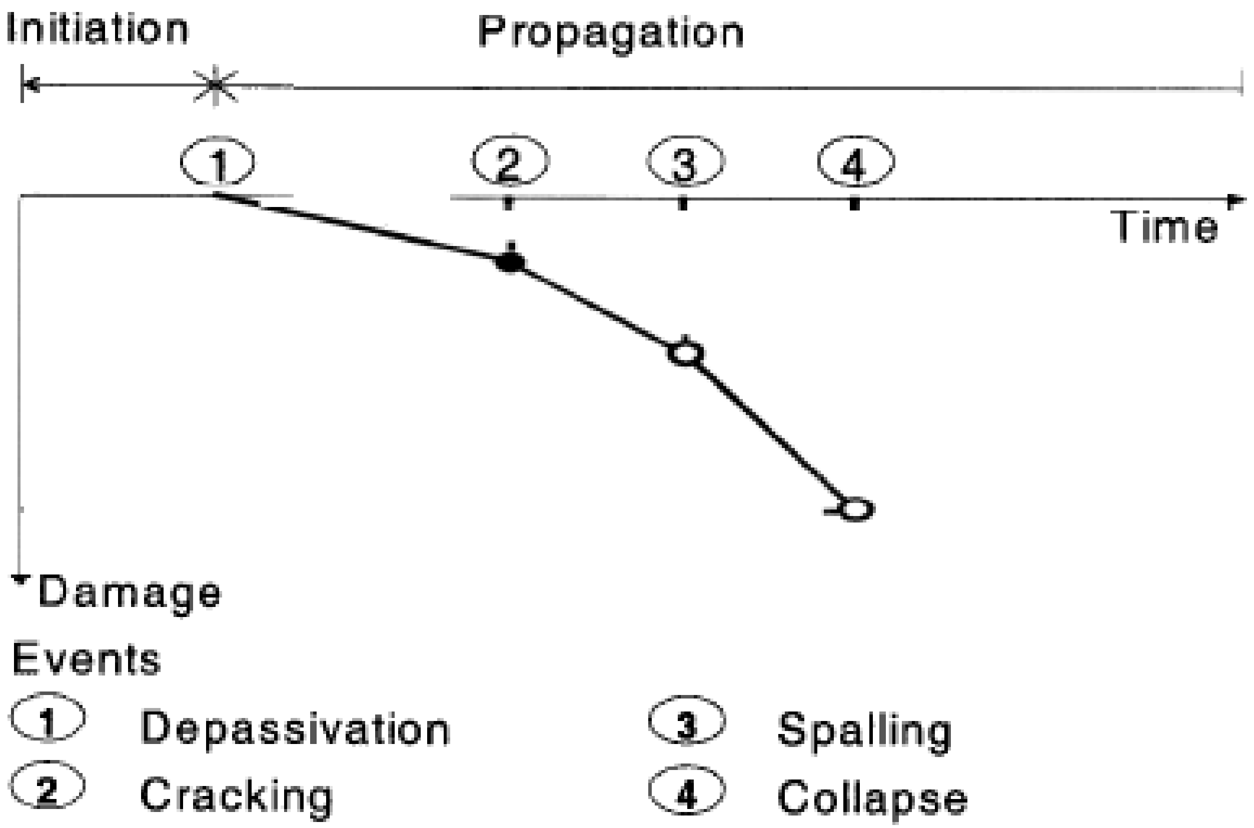
Deterioration

- 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)]

Deterioration Models / Limit States



Events related to the service life.

Durability Assessment Guides

- *fib* Bulletin 34*, "Model Code for Service Life Design" (fib, 2006)*
- Section 7.8 of the "*fib Model Code for Concrete Structures 2010*"
- SHRP 2 Renewal Project R19(A), *"Design Guide for Bridges for Service Life"*, Pre-publication Draft (TRB, 2013)

- All excellent Guides to developing Durability Assessments
  - But, are lacking in practical "How To" information for implementation in practice

Durability Assessment Tools

- *fib* Commission 5 is developing in-depth “How to” Bulletins on performing service life designs
  - Task Group 5.13 – Operational Documents to Support Service Life Design
  - Task Group 5.11 – Calibration of Code Deemed to Satisfy Provisions for Durability
  - Task Group 5.10 – Birth Certificate and Through-Life Management Documentation

Durability Assessment Tools

- SHRP 2 Project R-19(A) Next Phase
  - Promote Service Life Design Concepts & Technologies with AASHTO SCOBS T-9
    - Broad Marketing & Training Effort
    - Formal "Implementation Assistance Program"
    - Targeting Integration in 15% of Agencies by 2016
    - Produce Summary Guide
    - 3 Worked Example Service Life Designs

Service Life Design Strategies

- Avoidance of deterioration – Strategy A
- Design Based on Deterioration from the Environment – Strategy B
  - Deemed to satisfy provisions
  - Full probabilistic design
  - Semi-probabilistic or deterministic design

Avoidance of Deterioration

- Also called the “Design-Out” approach
- Achieved by either:
  - – Eliminating the environmental exposure actions
    - (e.g., interior of buildings with controlled temperature & humidity)
  - – Providing materials with resistance well beyond the requirements needed
    - (e.g., stainless steel reinforcement)

Deemed to Satisfy Method

- Prescriptive approach used in most major design codes
  - e.g., In severe environment, use concrete with w/c ratio < 0.40, 2½" cover
- Based on some level of past performance
- No mathematical deterioration modeling
- Simplistic and not quantifiable
- Lowest level of reliability

ACI-318 Durability Requirements

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
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
			Maximum water-soluble chloride ion (Cl^-) content in concrete, percent by weight of cement#		
			Reinforced concrete	Prestressed concrete	Related provisions
C0	N/A	2500	1.00	0.06	None
C1	N/A	2500	0.30	0.06	
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.

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 beyond typical experience level for most practicing bridge engineers
- Work effort may be regarded as too time consuming for standard structures
- Usually reserved for use on large projects
  - Most projects discussed at ASBI are large

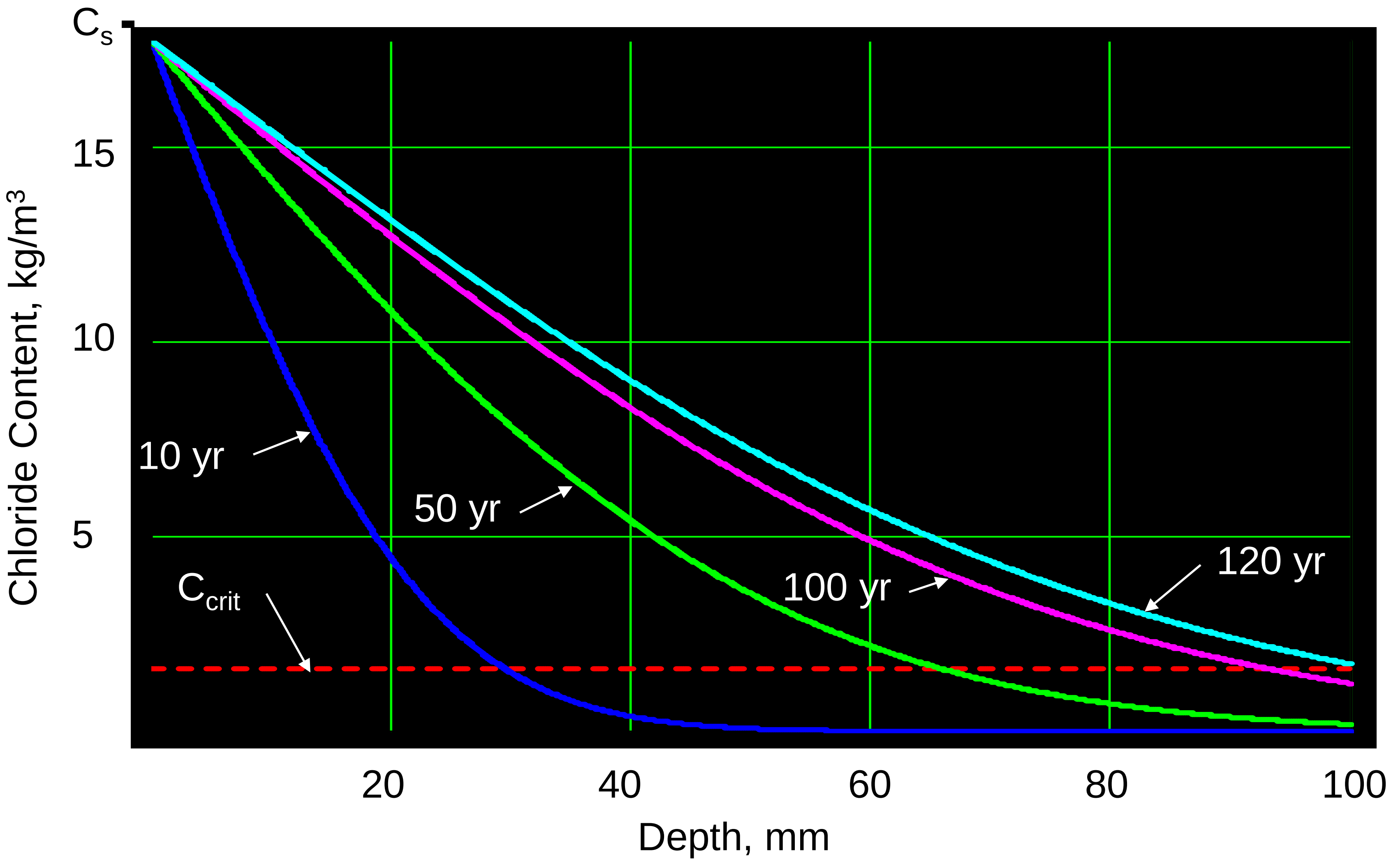
Deterioration – Chloride Ingress

- Fick's 2nd Law Models Time to Initiate Corrosion in Uncracked Concrete (Cracks < 0.3 mm or 0.012")

$$C(x,t) = C_o + \left(C_s - C_o\right)\cdot\left(1 - \mathrm{erf}\left(\frac{x}{2\cdot\sqrt{D_{app,c}\cdot t}}\right)\right) \leq C_{crit}$$

C(x,t)	Chloride concentration at depth & time	kg/m^3
x, t	Depth from surface / time	mm, yr
erf	Mathematical error function	-
C_{crit}	Critical chloride content (to initiate corrosion)	kg/m^3
C_o	Initial chloride content of the concrete	kg/m^3
C_s	Chloride concentration at surface	kg/m^3
$D_{app,C}$	Apparent coefficient of chloride diffusion in concrete	mm^2/yr

Chloride Profiles



Service Life Misconceptions

- Reinforced concrete elements are less durable than prestressed elements
  - Deterioration models for chloride ingress in the *fib* Bulletin 34 – MCSLD refer to “uncracked” concrete, defined as having cracks less than 0.3 mm or 0.012”
  - No bonus in the resistance for prestressing

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 Misconceptions

- Requiring a 100 year service life as part of an RFP is sufficient to achieve it

- Actually, much more definition is required
  - Design Guide / Code
  - Service Life Design Strategy
  - Reliability Performance Requirements
  - … etc.

Service Life Design Steps

- Identify Environmental Exposure Classes
- Select a Deterioration Limit State
  - (Depassivation, cracking, spalling, collapse)
- Select an Expected Service Life
- Select Design Guide / Code & Strategy
- Select a Level of Reliability Level
- Select Materials / Member Dimensions
- Produce Contract Documents

Contract Documents

- Identify Additional Tests and Data Collection Requirements
  - Concrete Coefficient of Chloride Diffusion
  - Inverse Effective Carbonation Resistance
  - Cover Dimension to Reinforcing Steel
- Incorporate Appropriate Tests in Contract Special Provisions
  - State the Extent of Concrete Test Samples Taken
  - State the Frequency of Cover Dimensions Taken
  - Identify Means to Deal With Variations from Design Intent

Construction Test Requirements

- Concrete Coefficient of Chloride Diffusion – Long Term Tests
  - **ASTM C1543/AASHTO T259** – Standard Test Method for Determining the Penetration of Chloride Ion into Concrete by Ponding (**Salt Ponding Test** – 28 day cure, 90 day exposure)
  - **Nordtest Method NT Build 443** – Accelerated Chloride Penetration (**Bulk Diffusion Test** – 28 day cure, 35 day minimum exposure, 90 days for higher quality concrete)
  - **Nordtest Method NT Build 355** – Chloride Diffusion Coefficient from **Migration Cell Experiments** (90 day cure)

Construction Test Requirements

- Concrete Coefficient of Chloride Diffusion – Short Term Tests
  - **ASTM C1202/AASHTO T 277** – Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration (**Rapid Chloride Permeability Test** – 56 day cure, ~24 hour conditioning, 6 hour test)
  - **AASHTO TP 64** – Predicting Chloride Penetration of Hydraulic Cement Concrete by the **Rapid Migration Procedure** (~24 hour conditioning, 18 hour test)
  - **Nordtest Method NT Build 492** – **Chloride Migration Coefficient** from Non-Steady State Migration Experiments (28 day cure, test duration 6 to 96 hours, usually 24 hours)

Construction Test Requirements

- Cover Meters for Steel Reinforcement Cover Measurements

- Complete Mapping
  – Min/Max Depth
- Calculate Parameters
  – Mean & Std. Deviation
- ACI 228.2R-2.51
- BSI 1881:204

Through Life Management

- Integrating All Stages in structure's life:
  - Design
  - Construction
  - Conservation (In-service Maintenance, Inspection and Intervention)
  - Dismantlement
- Future Oriented – Toward Sustainable, Life-Cycle Thinking

Service Life Stages

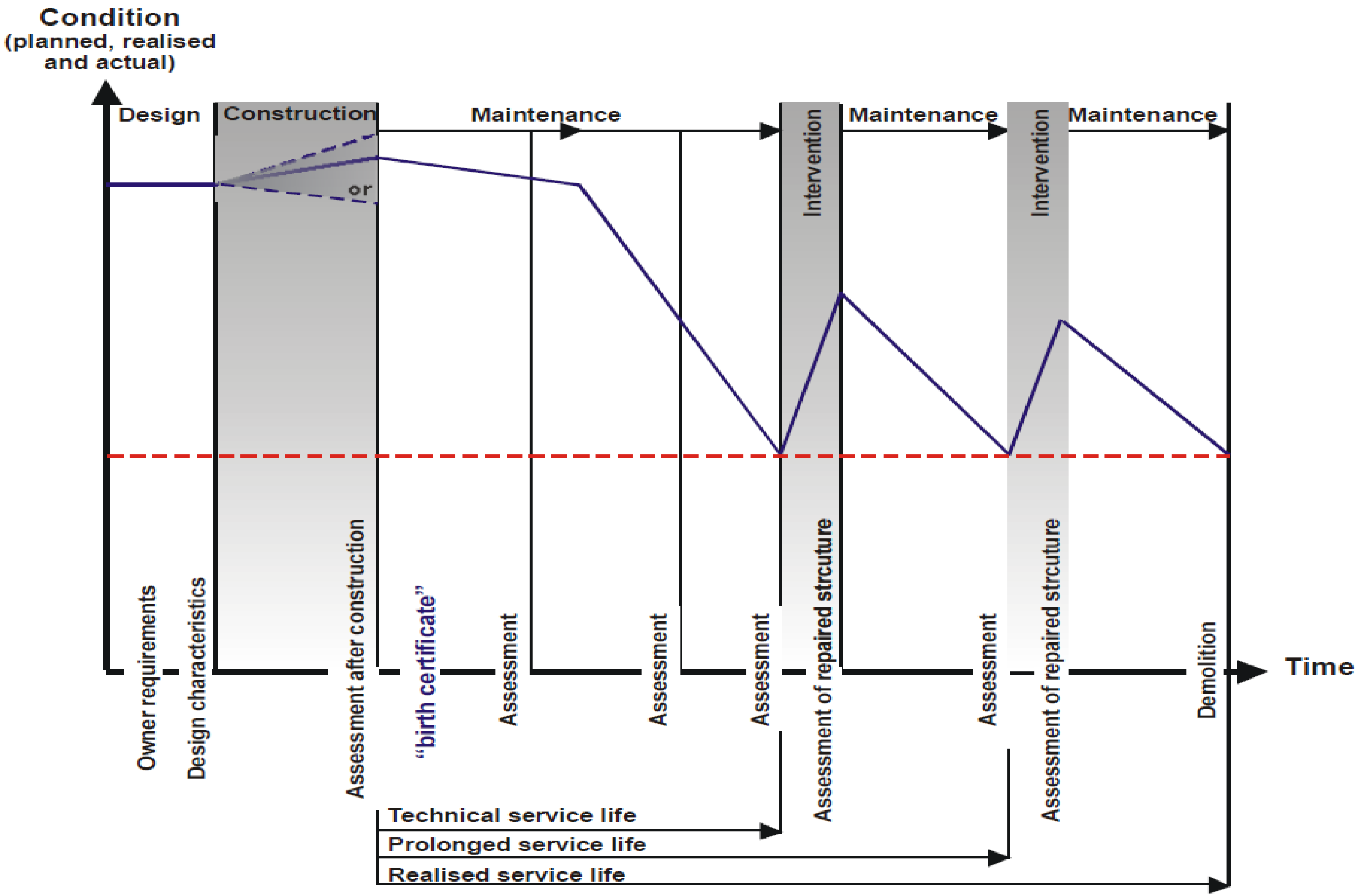


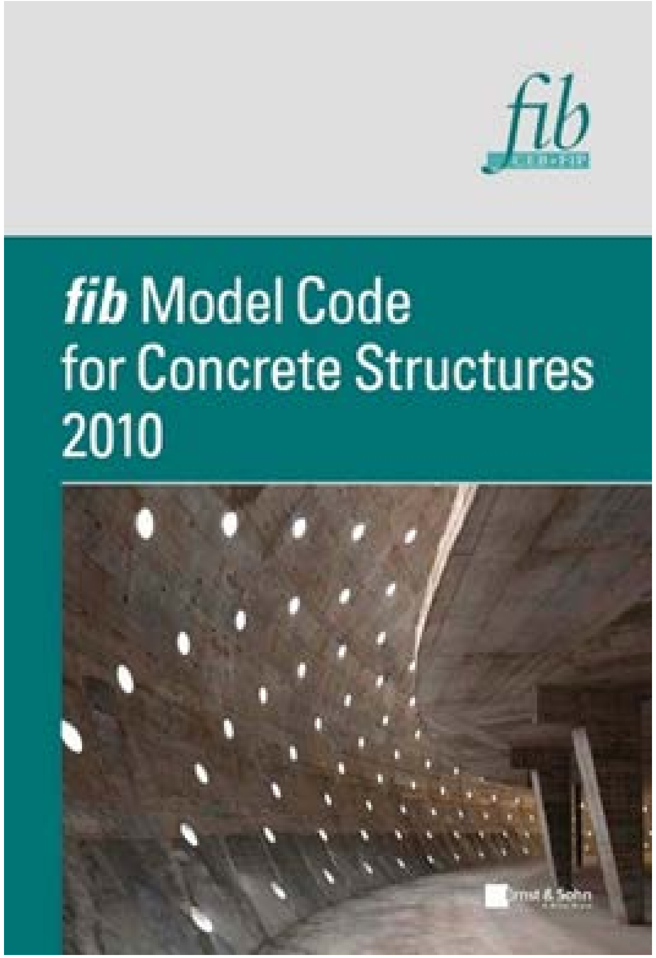
Fig. 2-1: Complete service life from birth to death, adapted from [28]

Inspection & Monitoring Plan

- Initial (End of Construction)
  - Birth Certificate documentation
- Routine Inspections (current ~ 2 yrs)
- Special Inspections (Scour, FCM)
- Damage (EQ, Flood, Fire, Collision)
- In-Depth Monitoring (~ 10-20 yr)
  - Chloride penetration tests
  - Depth of Carbonation tests

Birth Certificate Definition

- A <u>document</u>, report or technical file (depending on the size and complexity of the structure concerned) <u>containing engineering information</u> formally <u>defining</u> the form and the <u>condition</u> of the structure <u>after construction</u>.



Birth Certificate Purpose

- Documents parameters important to the durability & service life of the structure
- Provides means of comparing actual behavior/performance vs. design
- Facilitates ongoing (through-life) evaluation of the service life

Birth Certificate Purpose

- Outlines an Operational Schedule for:
  - Routine Maintenance
  - Regular Inspections
  - Durability Performance Monitoring
  - Replacement Activities

- Similar to an Automobile Owner's Manual

- Identifies Potential Demolition Schemes

Birth Certificate Process

- Initially Developed During Design Phase
  - Records the Intended Design
- Updated at Completion of Construction
  - As-Built Material Properties and Test Results
    - Concrete Classes / Mix Designs
    - Steel Reinforcement / Prestressing Grades
    - Chloride Diffusion Coefficient
    - Cover Dimensions
- Updated after Maintenance, Inspection & Long Term Performance Monitoring

Birth Certificate Table of Contents

- Asset Identification & Description
- Design & Construction Parameters
- Environmental Exposure Conditions
- Deterioration Mechanisms & Models
- Testing Requirements
- Structure & Replaceable Element Data
- In-Service Conservation Plan
- Dismantling Plan

BC Asset Identification

Identification of Asset

Owner	Public Works and Government Services Canada
Structure Classification	Bridge
Structure Name	Confederation Bridge (or Fixed Link)
Inventory ID #	XXX
Structure Description	11.6 m wide by 12.9 km long precast, post-tensioned segmental concrete structure with West and East Approaches and a Main Bridge Unit. Typical spans are 93 m for the Approaches and 250 m for the Main Bridge Unit.
Geographic Location	Carries NB 16/PEI 1 (Trans-Canada Highway) over Northumberland Straits between Borden–Carleton, PEI and Cape Jourimain, NB
Date Placed in Service	31-May-1997

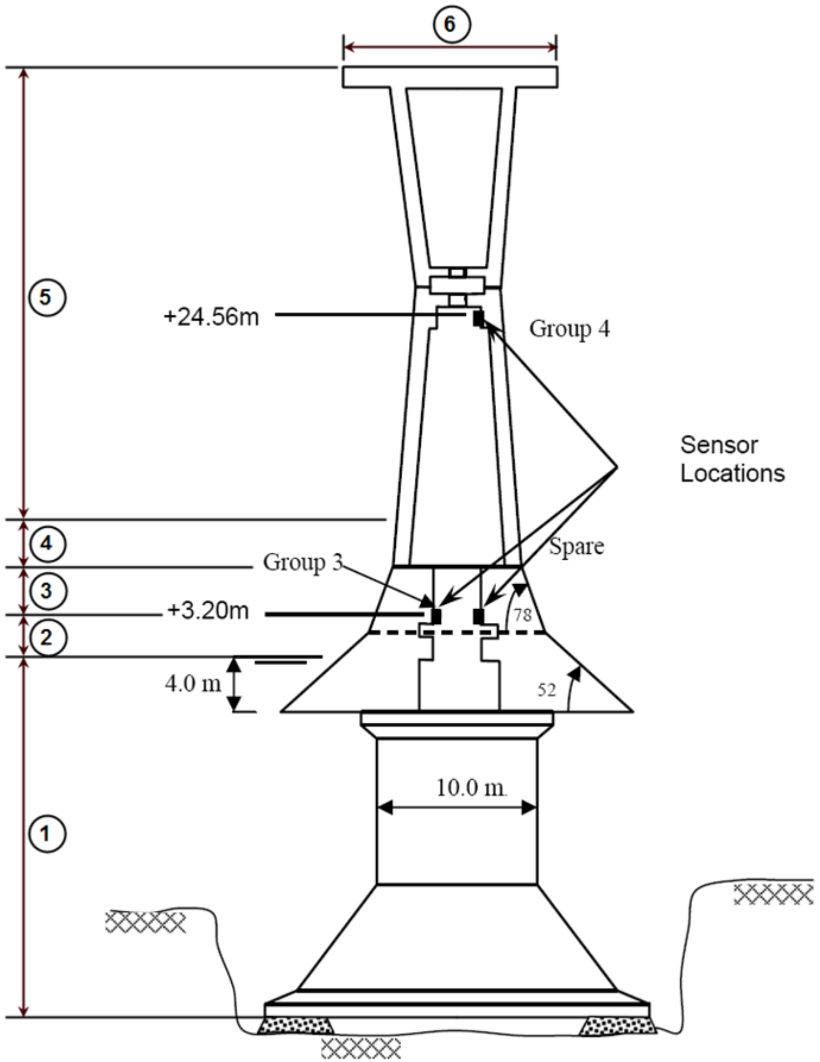
BC Design/Construction Parameters

Design Parameters		
Consequence Class (CC) of Failure or Malfunction	CC3 - High consequence for loss of human life, or economic, social or environmental consequences very great	(Table A2-1 of MC-SLD)
Design Supervision Level (DSL)	DSL3 - Extended Supervision (Third party checking: Checking performed by an organisation different to that which has performed the design)	(Table A4-1 of MC-SLD)
Service Life Design Strategy /	Strategy B - Providing resistance to the deterioration mechanisms active in the service environment	
Methodology	Method B4. A reliability-based methodology (Full probabilistic design)	
Primary Protection Strategies	Material's own resistance	
	Basic resistance using a single protection strategy	
Durability Limit State (DLS)	DLS1 - Depassivation of reinforcing	
Target Service Life	100 years	

BC Environmental Parameters

Environmental Parameters		
Macro-Environment	Coastal Marine	
Macro-Climate	Cold	
Mean High Temperature	28 °C	CHBDC CAN/CSA S6-88
Mean Low Temperature	-28 °C	"
Mean Relative Humidity	80%	"
Deterioration Mechanisms	Chloride Ingress	
	Freeze-Thaw	
	Ice Abrasion	
Exposure Classes	XS: Corrosion of reinforcement induced by chlorides from sea water	(EN 206-1)
	XD: Corrosion of reinforcement induced by chlorides other than from sea water	
	XF: Freeze - thaw attack upon concrete	

BC Environmental Parameters



Component	Figure ID	Exposure Class (EN206)
Substructure		
Submerged Zone	1	XS2
Tidal Zone	2	XS3
Splash Zone	3	XS3
Spray Zone	4	XS3
Atmospheric Zone	5	XS1
Superstructure		
Atmospheric Zone	5	XS1
Roadway & Traffic Barrier	6	XD3

BC Deterioration Models

BIRTH CERTIFICATE DOCUMENT
Deterioration Mechanisms & Models

Inventory ID	X10625
Structure Name	Hwy. 5 Overcrossing Hwy. 12
Deterioration Mechanism	Chloride ingress
Deterioration Model	Fick's 2nd Law
Source	fib Bulletin 34 - Model Code for Service Life Design

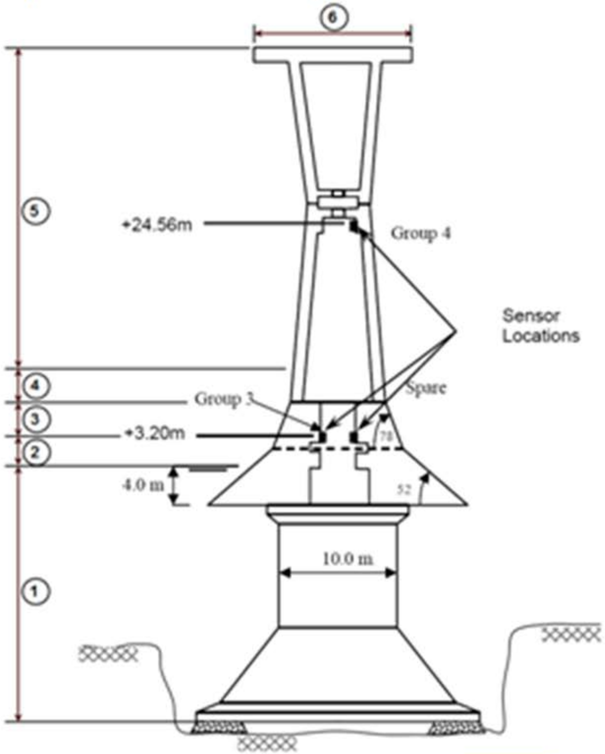
$$C_{crit} = C(x = cov, t) = C_o + (C_{s,\Delta x} - C_o)\cdot\left(1 - \operatorname{erf}\left(\frac{cov - \Delta x}{2\cdot\sqrt{D_{app,C}\cdot t}}\right)\right)$$

Function Variables	Description	Units
t	Time	[yr]
x	Depth with corresponding content of chlorides C(x,t)	[mm]
C_{crit}	Critical chloride content	[wt.-%/c]
C_o	Initial chloride content of the concrete	[wt.-%/c]
$C_{s,\Delta x}$	Chloride concentration at surface or a depth Δx	[wt.-%/c]
Δx	Depth of the convection zone (concrete layer, up to which the process of chloride penetration differs from Fick's 2nd law of diffusion)	[mm]
cov	Concrete cover	[mm]
$D_{app,C}$	Apparent coefficient of chloride diffusion through concrete	[mm^2/yr]

BC Structure Component Data

Structure Component Monitoring

Inventory ID	XXX
Structure Name	Confederation Bridge (or Fixed Lin
Component Name	Pier
Location	# 20
Deterioration Model	Fick's 2nd Law



Sub-Component	Figure ID	Status	Exposure		Concrete			Reinforcing Steel		C_{crit} [kg/m³]	Remaining Service Life [yrs]
			Class	$C_{s,\Delta x}$ [kg/m³]	Class/ Grade [MPa]	C_i [kg/m³]	$D_{app,C}$ [mm²/yr]	Type/ Grade [MPa]	cov [mm]		
Ice Shield, splash zone	3	Design	XS3	17.7	HPC/55	0	15.1	Plain/400	100	1.59	115
		As-Built	XS3	17.7	HPC/55	0.085	15.324	Plain/400	95	1.59	100
		In-Service									
		#1 (10 yr)	XS3	17.04	HPC/55	0.05	15.7	Plain/400	95	1.59	99

BC Maintenance Schedule

Structure Name	Confederation Bridge (or Fixed Link)		**Initials**		
Inventory ID #	XXX		**Actual Date**		
Geographic Location	Carries NB 16/PEI 1 (Trans-Canada Highway) over Northumberland Straits between Borden–Carleton, PEI and Cape Jourimain, NB		**Sched. Date**	31-Aug-97	3-Mar-98
Date Placed in Service	31-May-97		**Yr**	1	
Routine Maintenance Action	**Location/Component**	**Frequency**			
Clean / Clear					
Sweep roadway deck surface		6 months			
Clear bridge deck drains		6 months			
Flush drainage piping		6 months			
Pressure wash		1 year			
Clean abutment seats		1 year			

Existing Structures

- Principles from Service Life Design can be extended to Existing Structures to:
  - Evaluate Current Condition
    - Take cores to measure actual chloride profiles, or depth of carbonation
    - Extrapolate material durability properties and environmental action parameters
  - Estimate Remaining Service Life
    - Fit the data to the mathematical deterioration model
    - Calculate end of service life

Existing Structures

- Difficulties in Estimating Remaining Service Life
  - Determining Concrete Durability Properties
    - No initial testing of chloride diffusion coefficient
    - No initial data on the environmental parameters
  - Requires Taking Cores to Develop Chloride Profiles
    - What frequency?
    - Does patching the sampling area cause more durability issues?

Existing Structures

- Work of R19-A Scope is for the Design of New Structures to Achieve 100-year Service Life or Beyond

- Implementation Plan will Focus on New Designs

Review Summary

- Service Life Designs are being required by Owners
- Service Life Design Guide Specifications are available
- Implementation Plan and “How To” examples are being developed
- Birth Certificate provides a means for collecting data for future development of deterministic code provisions

Questions?

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http://www.fhwa.dot.gov/goSHRP2/

http://shrp2.transportation.org