


SHRP2 SOLUTIONS
STRATEGIC HIGHWAY RESEARCH PROGRAM

Introduction to Service Life Design of Bridges

IBC Workshop: W-8 Service Life Design

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U.S. Department of Transportation
Federal Highway Administration

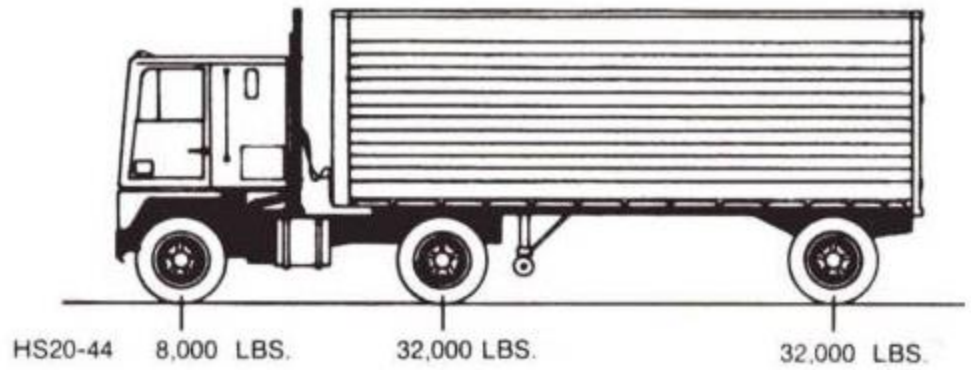
American Association of State Highway and Transportation Officials
AASHTO

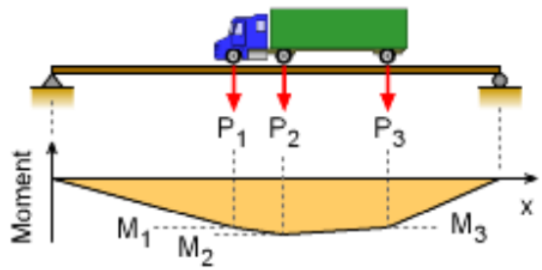
Presentation Overview

- Service Life Design – What is it?
- Historical Background – What's been done?
- Current Status / Gaps – What's being done?
- Proposed Research on Service Life Design – What's next?

Service Life Background

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



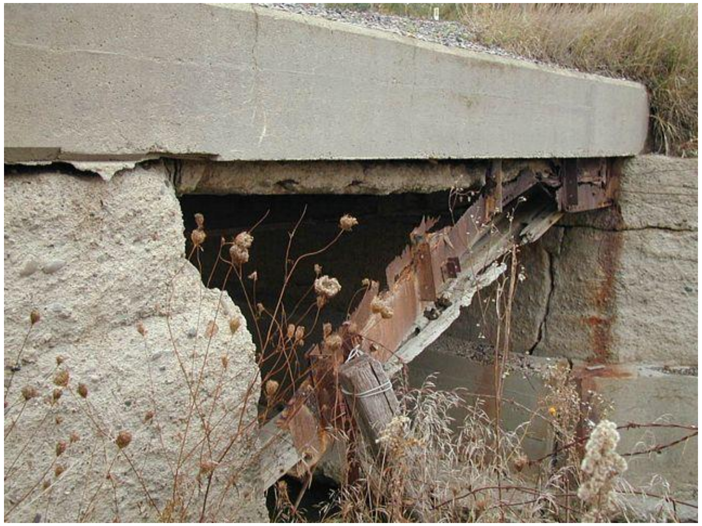


Typical Moment Diagram for a Series of Point Loads

  - 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
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‡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.

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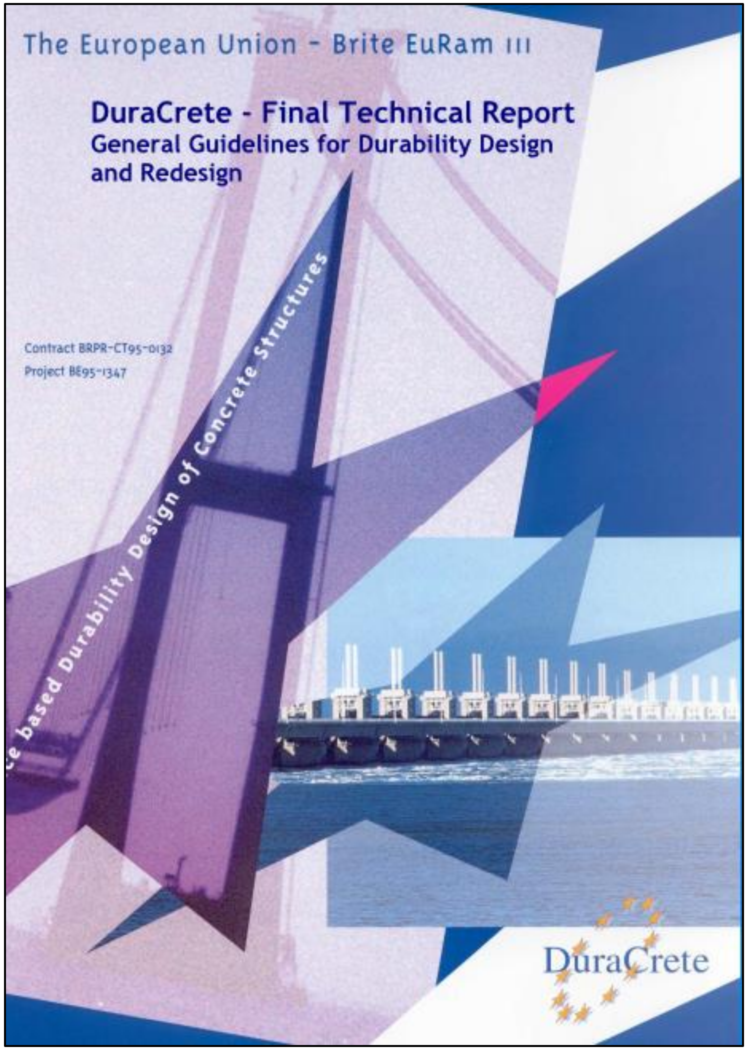
ACI 365.1R-00 became effective January 10, 2000.



Common Deterioration Types

- Reinforcing Steel Corrosion
- Concrete Cracking, Spalling, Delamination

- Structural Steel Corrosion following breakdown of Protective Coating Systems

Other Deterioration Types

- Alkali-Aggregate Reaction (ASR, ACR)

- Delayed Ettringite Formation (DEF)

Other Deterioration Types

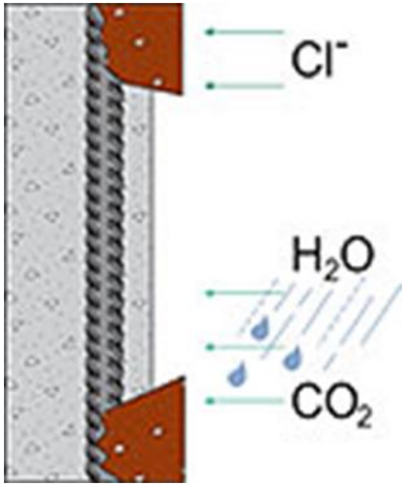
- Freeze-Thaw

- Sulfate Attack

- Salt Scaling

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)



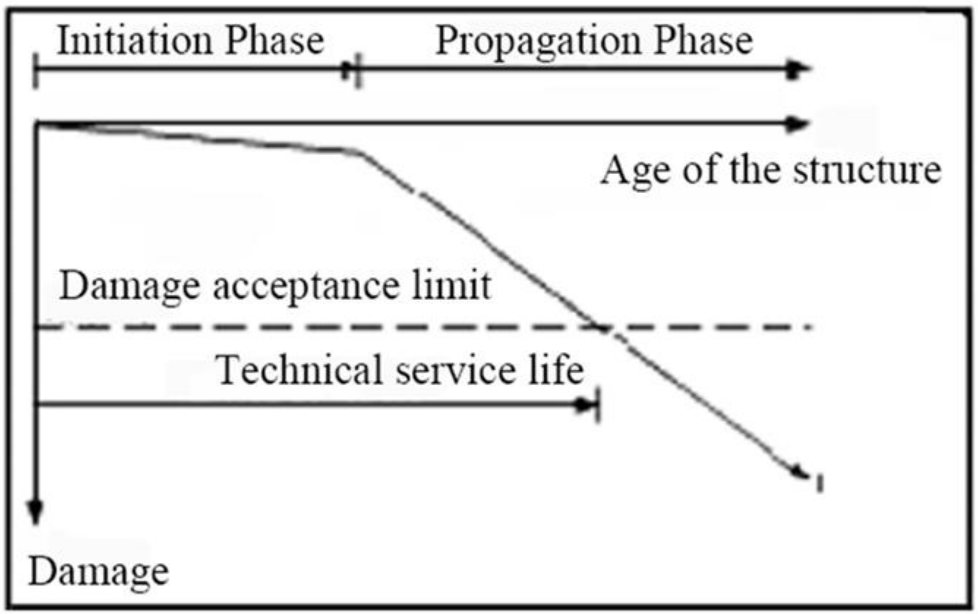
Material Resistance

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

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

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)]

Deterioration Limit States

- End of Service Life defined by Damage Limit State
- For Reinforced Concrete there are 4 limit states
  - Corrosion Initiation (depassivation)
  - Cracking of concrete from expansion of corrosion by-products
  - Spalling of surface concrete
  - Loss of reinforcing cross section / collapse
- Current practice – Corrosion Initiation is end of life

Example Deterioration Model

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

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

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

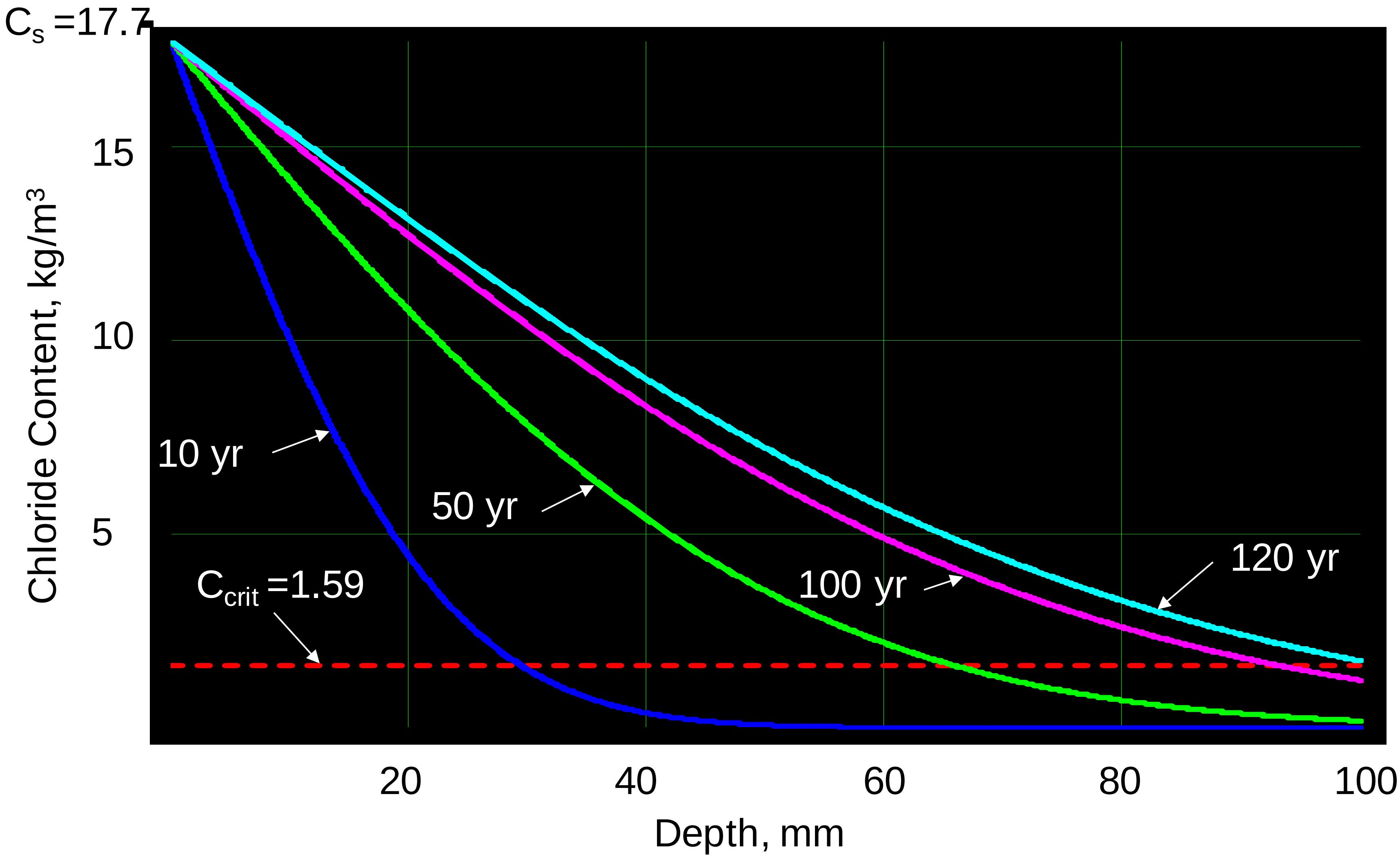
$$k_e = \exp\left(b_e\left(\frac{1}{T_{ref}} + \frac{1}{\mathbf{T_{real}}}\right)\right)$$

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

- **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

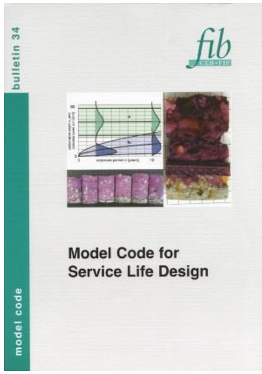
Chloride Profiles vs. Age

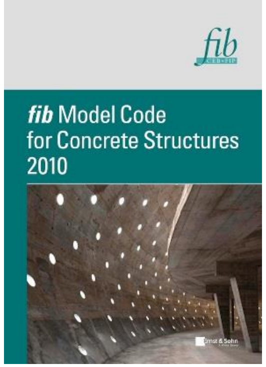
constant $D_{app,c}$ = 15.1 mm^2/yr



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

Through-Life Management

- Integrating all stages in the life of a structure
  - Design
  - Construction
  - In-Service Maintenance & Inspection
  - Intervention (Repair & Rehabilitation)
  - Dismantling
- Future oriented toward sustainable, life-cycle thinking

Through-Life Stages

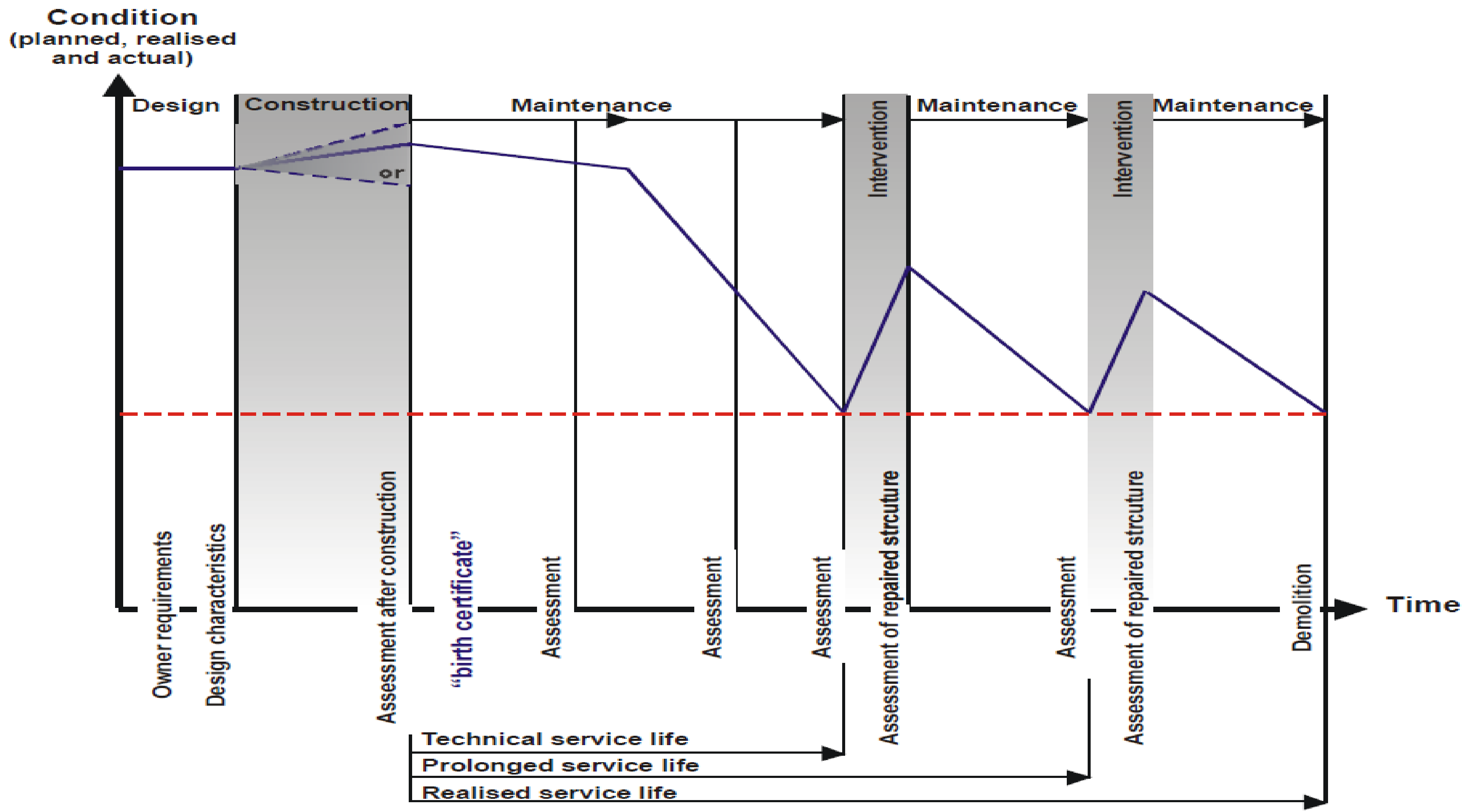


Fig. 2-1: Complete service life from birth to death, adapted from [28]

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 or deterministic design
- “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, 5.10.1 and 5.14
- 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

- 5.10.1 – Concrete Cover
  - Cover for unprotected prestressing and reinforcing steel shall not be less than that specified in Table 5.10.1-1 and modified for *W/C* ratio…
  - Modification factors for *W/C* ratio shall be the following:
    - For W/C ≤ 0.4 ………………………………………….. 0.8
    - For W/C ≥ 0.5 ………………………………………….. 1.2

AASHTO LRFD Provisions

- Specified concrete cover dimensions

Table 5.10.1-1—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

AASHTO LRFD Provisions

- 5.14 – Durability
  - 5.14.1 – Design Concepts
    - Concrete structures shall be designed to provide protection of the reinforcing and prestressing steel against corrosion throughout the life of the structure.

- Again, not very much guidance

AASHTO LRFD Durability Provisions

- 5.14.1 – Design Concepts
  - Special requirements that may be needed to provide durability shall be indicated in the contract documents.
    - air-entrainment of the concrete
    - epoxy-coated or galvanized reinforcement
    - stainless steel bars… or nonferrous bars
    - sealing or coating
    - special concrete additives
    - special curing procedures
    - low permeability concrete

AASHTO LRFD Durability Provisions

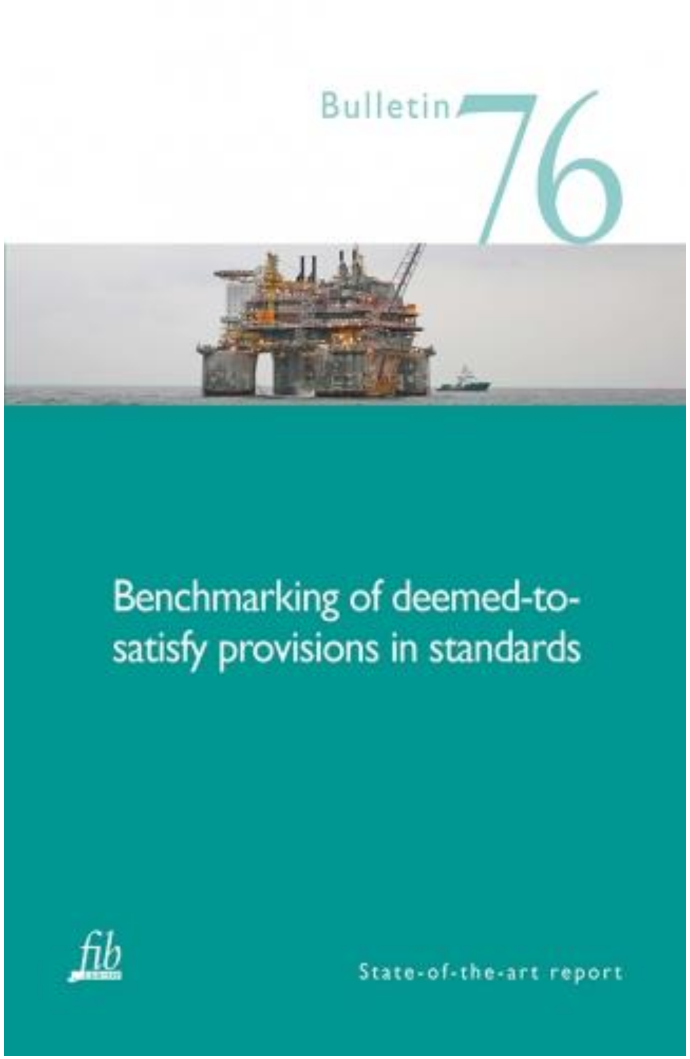
- Table C5.14.2.1-1 – New in LRFD 8th Edition

Table C5.14.2.1-1—Factors in Concrete Durability

Type of Materials-Related Defect	Surface Distress Manifestations and Locations	Cause or Mechanisms	Time of Appearance	Prevention or Reduction
Due to Physical Mechanisms				
Mechanical wear of decks and wearing surfaces decks and wearing surfaces	Abrasion and polishing polishing, rutting	Tire contact, improper curing, water floating to surface	Varies	Proper curing, sealants
Due to Chemical Mechanisms				
Corrosion of embedded steel	Spalling, cracking, and deterioration at areas above or surrounding embedded steel.	Chloride ions penetrate concrete and corrode embedded steel.	3–10 years	Reducing the permeability of the concrete, providing adequate concrete cover, and coating steel.

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	$\beta = -\phi_U^{-1}(P_f)$	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

where $-\phi_U^{-1}(P_f)$ is defined as the inverse standard normalized distribution function

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

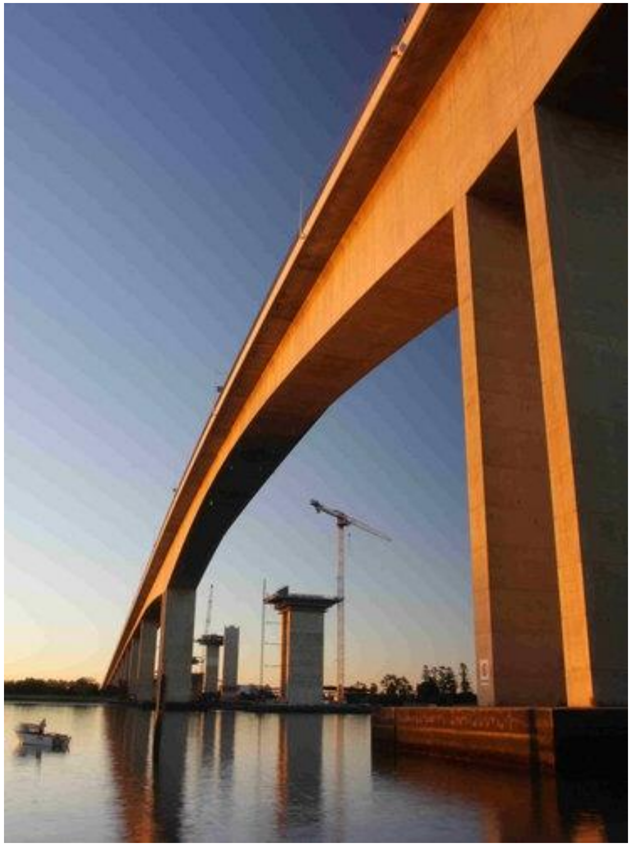
- Confederation Bridge, Canada –1997 (100 years)

Service Life Designed Structures

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

Service Life Designed Structures

- Gateway Bridge, Brisbane – 2010 (300 years)



Service Life Designed Structures

- Ohio River Bridge, KY – 2016 (100 years)

Service Life Designed Structures

- Tappan Zee Bridge, NY – 2018 (100 years)

courtesy of New York State Thruway Authority

Need More Focus on These

- Representing the majority of the 600,000+ bridges in the US

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

SHRP2 R19A Team

RESEARCH – **TRB**

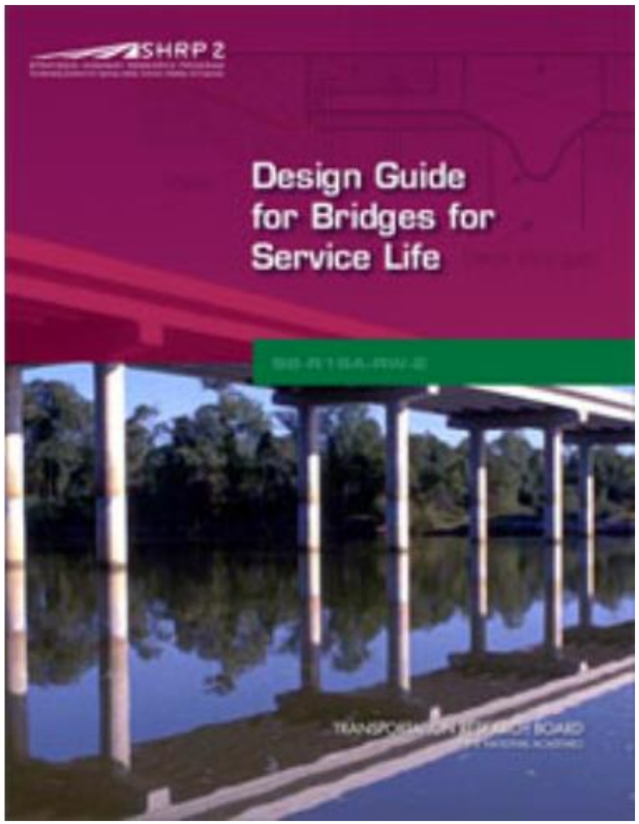
IMPLEMENTATION – **FHWA/AASHTO**

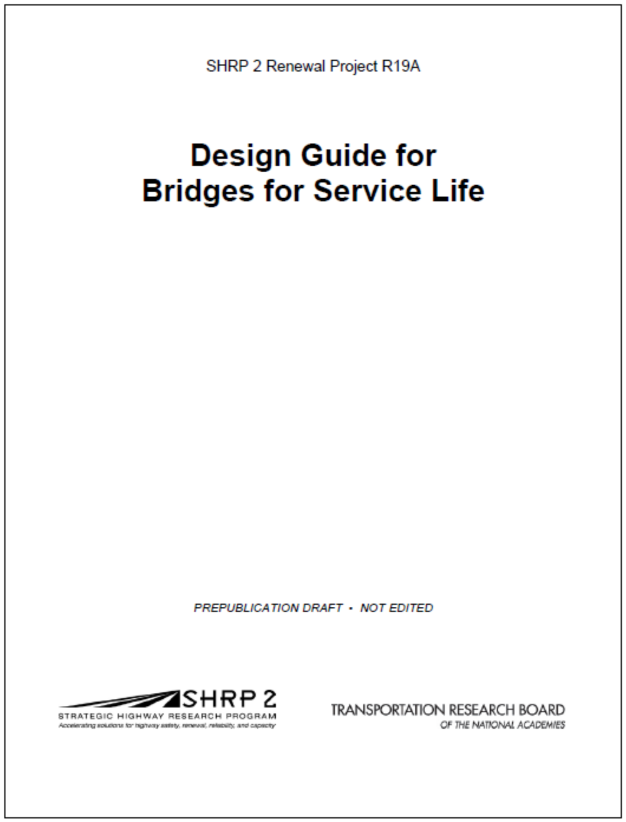
SUBJECT MATTER EXPERTS / LOGISTICS SME LEAD – **Jacobs**
TECHNICAL SMEs – **COWI**

LEAD ADOPTER AGENCIES

Research Work Completed

- Project R19A – Service Life Design Guide




SHRP 2 Renewal Project R19A

Design Guide for
Bridges for Service Life

PREPUBLICATION DRAFT • NOT EDITED

SHRP 2
STRATEGIC HIGHWAY RESEARCH PROGRAM

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

  - http://www.trb.org/Main/Blurbs/168760.aspx

IAP Round 4 Lead Adopters

- FHWA Central Federal Lands
  - Bonnie Klamerus, Mike Voth
- Iowa DOT
  - Ahmad Abu-Hawash, Norm McDonald
- Oregon DOT
  - Bruce Johnson, Paul Strauser, Zach Beget, Ray Bottenberg, Andrew Blower, Craig Shike
- Pennsylvania DOT
  - Tom Macioce
- Virginia DOT
  - Prasad Nallapaneni, Soundar Balakumaran

IAP Round 7 Lead Adopters

- Iowa DOT
  - Ahmad Abu-Hawash
- Maine DOT
  - Dale Peabody

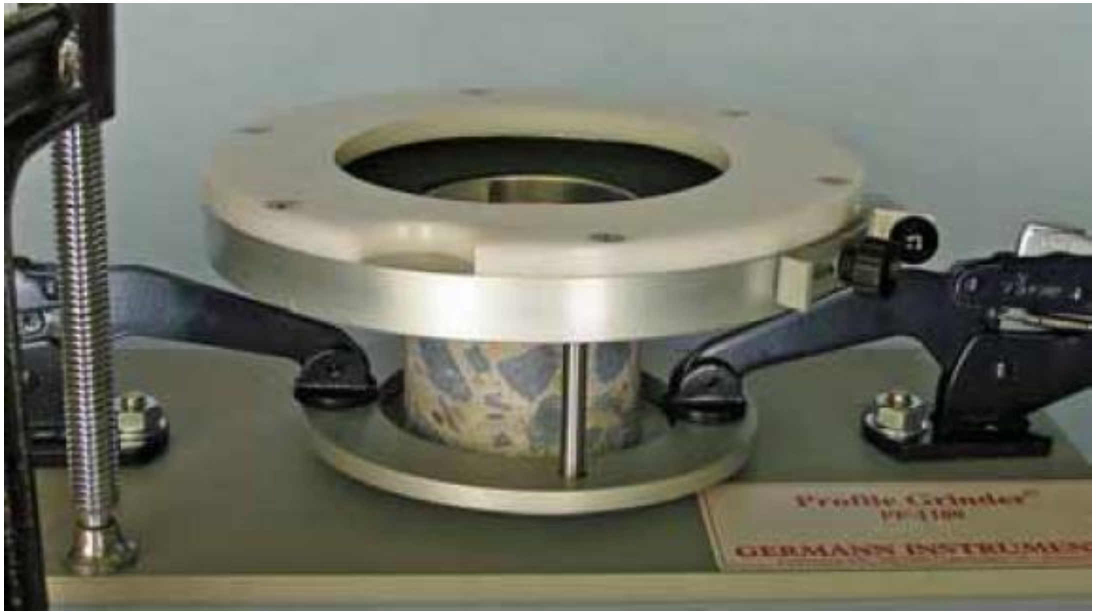
Current R19A Work Focus Areas

- Performing tests on material durability properties of concrete mix designs
  - Concrete chloride migration coefficient (NT Build 492)
  - Measurement of as-constructed concrete cover

Elcometer

Current R19A Work Focus Areas

- Tests on existing bridges to assess environmental loading and material behavior
  - Taking concrete cores to measure chloride loading from de-icing chemicals or sea water



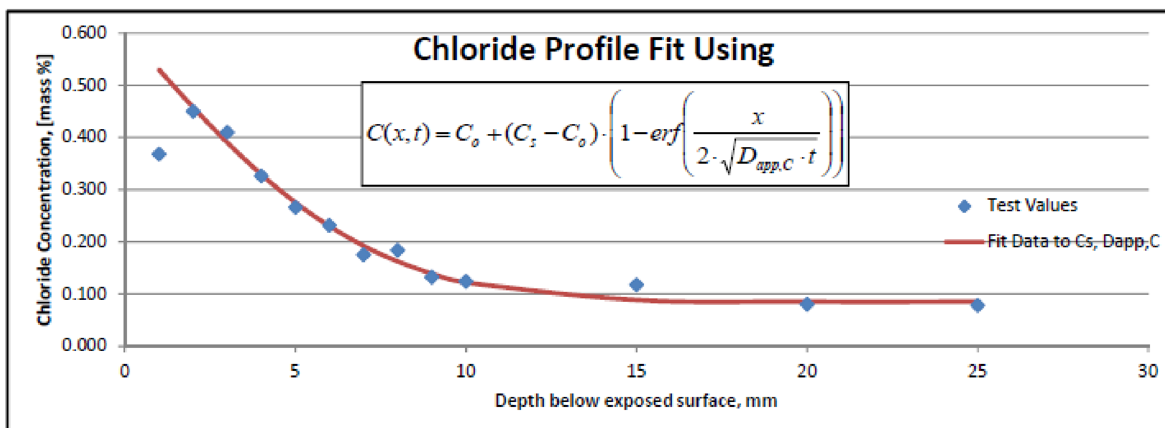
Source: Germann Instruments

Current Work Focus Areas

- Developing design tools and processes to aid in SLD
  - Excel spreadsheet for chloride profiling

d	depth from surface	[mm]	1	2	3	4	5	6	7	8	9	10	15	20	25	
C_m	Test Values	[mass %]	0.368	0.450	0.410	0.326	0.266	0.231	0.175	0.183	0.132	0.124	0.117	0.080	0.078	
C_c	Fit Data to C_s, $D_{app,C}$	[mass %]	0.530	0.458	0.391	0.329	0.275	0.230	0.192	0.162	0.139	0.122	0.089	0.085	0.085	$\sum (C_m - C_s)^2$
$(C_m - C_s)^2$	Sum of least squares			6.72E-05	3.76E-04	1.10E-05	9.01E-05	1.55E-06	2.93E-04	4.34E-04	5.00E-05	4.66E-06	8.12E-04	2.66E-05	4.90E-05	2.22E-03

C_o	Initial chloride content (measured)	[mass %]	0.085
t	Exposure time	[yr]	1
C_s	Chloride content at exposed face	[mass %]	0.605
$D_{app,C}$	Apparent coefficient of chloride diffusion	[mm^2/yr]	15.324



Full Probabilistic Tool - Input

				Normal Distr Coefficients		
Parameter	**Description**	**Units**	**Distribution Function**	**Mean, μ**	**Std Dev, σ**	**Coeff of Variation, σ/μ**
$D_{RCM,0}$	Chloride Migration Coefficient (from Nordtest NT Build 492 - results are given in m^2/sec)	in^2/yr	Normal	0.420	0.084	0.20
		mm^2/yr		271.0	54.2	
		m^2/sec		8.59E-12	1.72E-12	
b_e	Regression variable, (limited to 3500 °K to 5500 °K)	°K	Normal	4800	700	
T_{real}	Temperature (from Local Weather Data)	°F	Normal	49.1	12.06	
		°C		9.5	6.70	
		°K		282.65	6.70	
T_{ref}	Standard test temperature	°F	Constant	67.6		
		°C		19.8		
		°K		292.9		
k_e	Environmental transfer variable	n/a	n/a			
k_t	Transfer parameter	n/a	Constant	1.0		
α	Aging exponent - All types in atmospheric zone	n/a	Beta	0.65	0.15	
t_o	Reference point of time (28 days = 0.0767 yrs)	yrs	Constant	0.0767		
A(t)	Aging function	n/a	n/a			
C_o	Initial Chloride Content of Concrete	mass% of binder	Normal	0.10	0.00	0.001
C_s or $C_{s,\Delta x}$	Chloride Concentration at surface, or at substitute surface Δx	mass% of binder	Log-Normal	3.00	1.50	0.50

Monte Carlo Trial Results

Trial Results of Randomly Generated Values of Input Parameters to Fick's 2nd Law

Trial	$D_{RCM,0}$ (mm^2/yr) rand 0-1	$D_{RCM,0}$ (mm^2/yr) RESULT	b_e (°K) rand 0-1	b_e (°K) RESULT	T_{real} (°K) rand 0-1	T_{real} (°K) RESULT	k_e	α rand 0-1	α RESULT	$A(t_{SL})$	cover (mm) rand 0-1	cover (mm) RESULT	C_{crit} (mass% of binder) rand 0-1	C_{crit} (mass% of binder) RESULT	$C(x=cov,t_{SL})$ RESULT	Pass (1) /Fail (0)
1	0.392	256.08	0.117	3967	0.918	292.0	1.0	0.921	0.853	0.0022	0.528	50.9	0.788	0.716	0.10	1
2	0.924	348.42	0.607	4990	0.690	286.0	0.7	0.236	0.541	0.0207	0.411	49.0	0.372	0.538	0.46	1
3	0.547	277.42	0.325	4482	0.682	285.8	0.7	0.473	0.650	0.0094	0.005	36.5	0.666	0.654	0.55	1
4	0.510	272.31	0.118	3970	0.025	269.5	0.3	0.094	0.439	0.0430	0.432	49.3	0.240	0.486	0.27	1
5	0.422	260.27	0.379	4585	0.203	277.1	0.4	0.757	0.766	0.0041	0.172	44.8	0.517	0.592	0.10	1
6	0.995	412.47	0.158	4099	0.160	276.0	0.4	0.935	0.864	0.0020	0.520	50.7	0.623	0.635	0.10	1
7	0.965	369.00	0.104	3920	0.320	279.5	0.5	0.398	0.619	0.0118	0.336	47.8	0.511	0.590	0.15	1
8	0.654	292.43	0.844	5500	0.626	284.8	0.6	0.102	0.447	0.0406	0.782	55.5	0.296	0.509	0.71	0
9	0.899	340.12	0.979	[illegible]	0.223	277.5	0.4	0.136	0.475	0.0330	.266	46.6	0.112	0.424	0.43	0
4999	0.892	338.07	0.897	5500	0.238	277.9	0.4	0.610	0.705	0.	0.116	43.4	0.279	0.502	0.10	1
5000	0.911	344.10	0.347	4524	0.702	286.2	0.7	0.865	0.819	0.00	0.805	56.1	0.669	0.655	0.10	1

SUMMARY

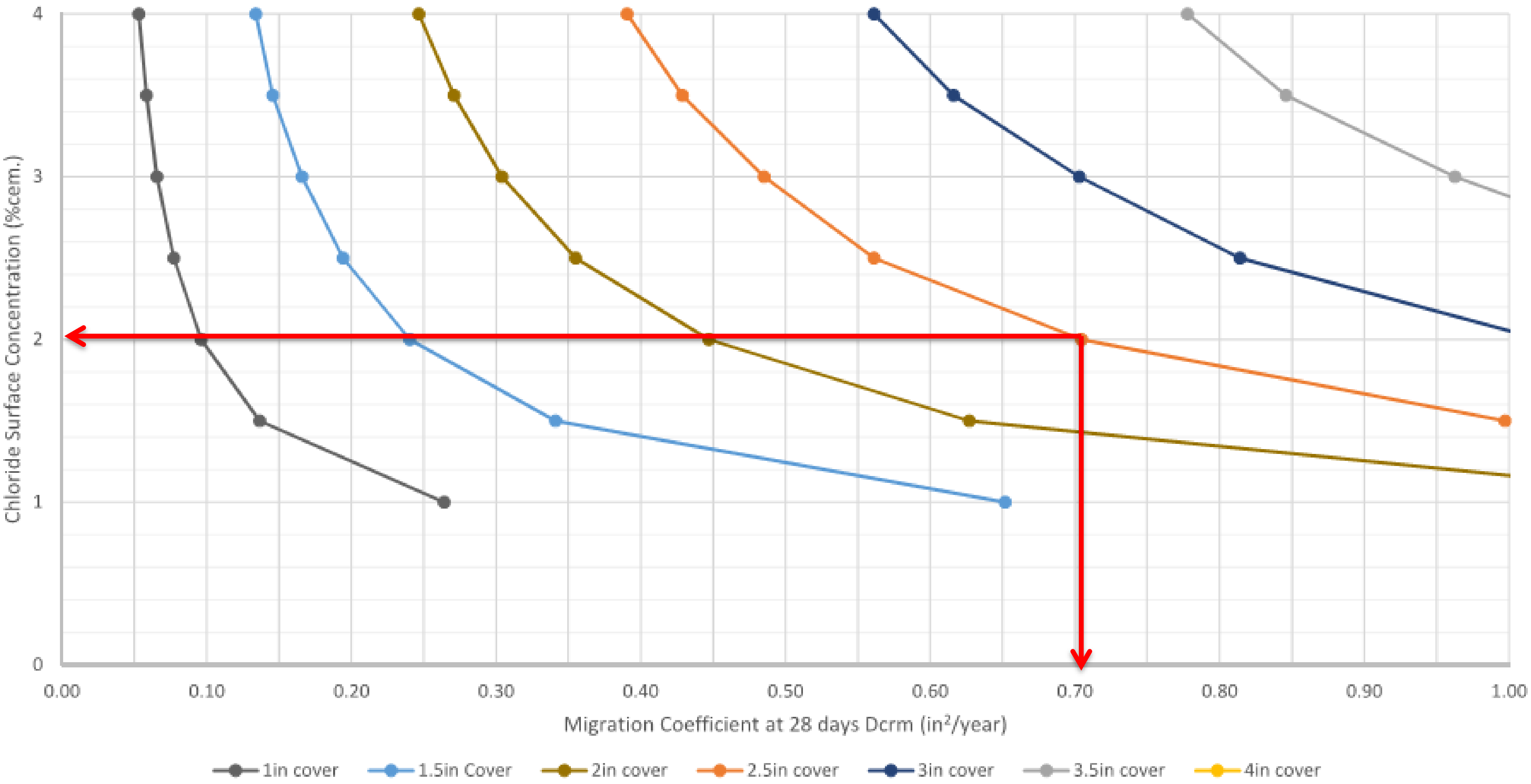
	$D_{RCM,0}$	b_e	T_{real}	k_e	α	$A(t_{SL})$	cover	C_{crit}
Computed Mean	270.47	4740	282.6	0.6	0.65	0.0	50.76	0.60
Input Mean	270.97	4800	282.7		0.65		50.80	0.60
Max	469.64	5500	309.08	2.41	1.00	0.	76.30	1.21
Min	92.56	3500	259.46	0.10	0.09	0.0	32.65	0.24

Total Passing	4526	
Total # of Trials	5000	
Reliability	0.91	
P_f, Probability of failure	0.09	
β, Reliability Index (calculate	1.312	Passes
β, Target Reliability Index	1.3	

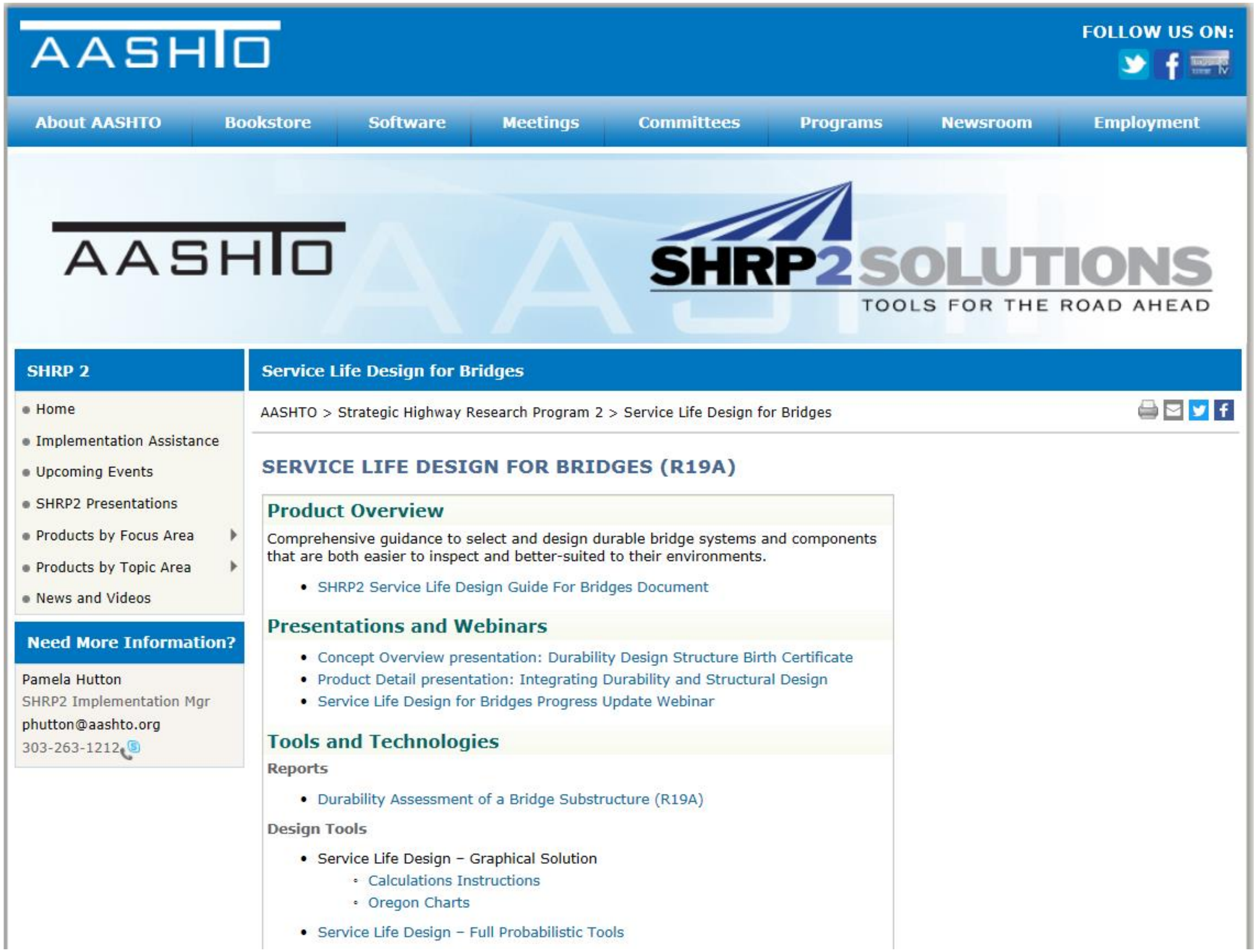
SERVICE LIFE DESIGN - GRAPHICAL SOLUTION

Calculations as per fib Bulletin 34 - fully probabilistic design
Service Life = 100 years
Beta = 1.3, Probability of failure = 10%
Critical chloride concentration: black bars - 0.6%cem.
Initial chloride concentration : 0.1%cem.

Temperature: mean = 49.1F, std = 12.1F
Exposure Zones: Buried/Submerged
Concrete Type: OPC + >20%FA



Implementation Products – Dedicated Webpage



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

Tools/Activities

- Completed final workshops in PA, VA, OR
- Academic Toolbox – guide for university professors to teach basic principles of SLD design (in final editing)
- IBC Workshop Today – Worked SLD example bridge
- 5 Peer Exchanges – first one being scheduled for July, 2018 in Oregon

Tools/Activities

- Develop 2 complete SLD Design Examples
  - Steel bridge in de-icing environment in NE US
  - Prestressed concrete bridge in coastal environment in SE US
  - Other deterioration types will be documented (AAR, DEF, freeze-thaw, coating failure, etc.)
- Develop calculations to determine example load and resistance factors to be used with chloride deterioration model

Tools/Activities

- Develop 2 RFP example specifications for design-build projects
  - Multiple conventional highway bridges on a new or reconstructed corridor project
  - Major bridges (segmental, arch, cable-stayed)

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
- Current implementation
  - SHRP2 R19A projects (FHWA CFL, IA(2), ME, OR, PA, VA)
- AASHTO T-9 Initiated Research
  - NCHRP 12-108 Uniform Service Life Design Guide

Questions?

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Resource: AASHTO's R19A Product Page

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