


SHRP2 SOLUTIONS
STRATEGIC HIGHWAY RESEARCH PROGRAM

Service Life Design of Bridges

PennDOT Workshop – Harrisburg, PA

Mike Bartholomew, P.E.
Technology Director, North American Bridges
CH2M

August 16, 2016

U.S. Department of Transportation
Federal Highway Administration

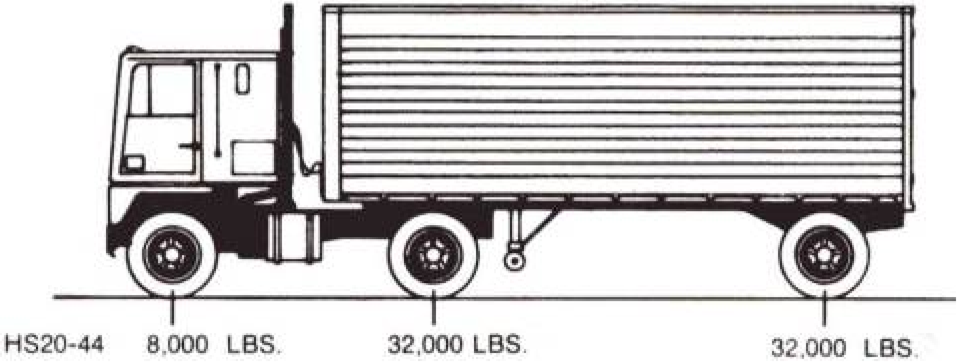
American Association of State Highway and Transportation Officials
AASHTO

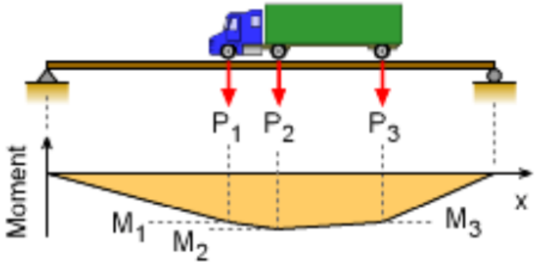
Presentation Overview

- 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 primarily from 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

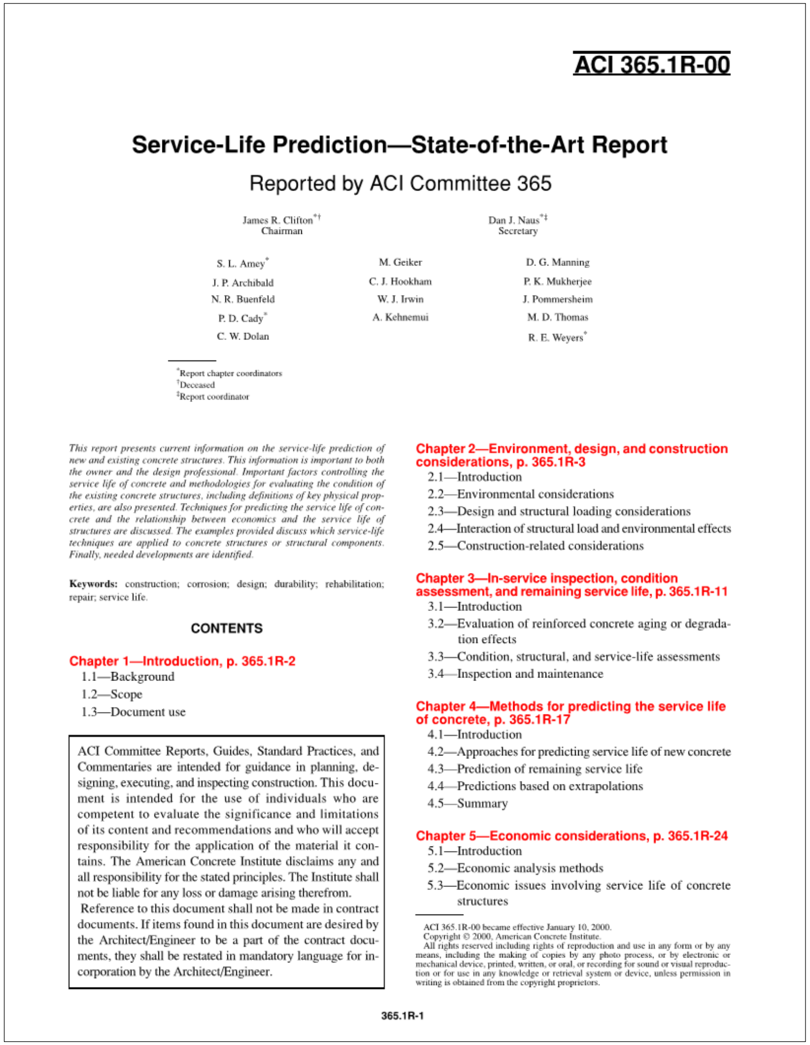
- **Owners** – Need assurance that a long-lasting structure will be designed, built, and operated (Effective use of public funding $$)

- **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

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C. W. Dolan · 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.

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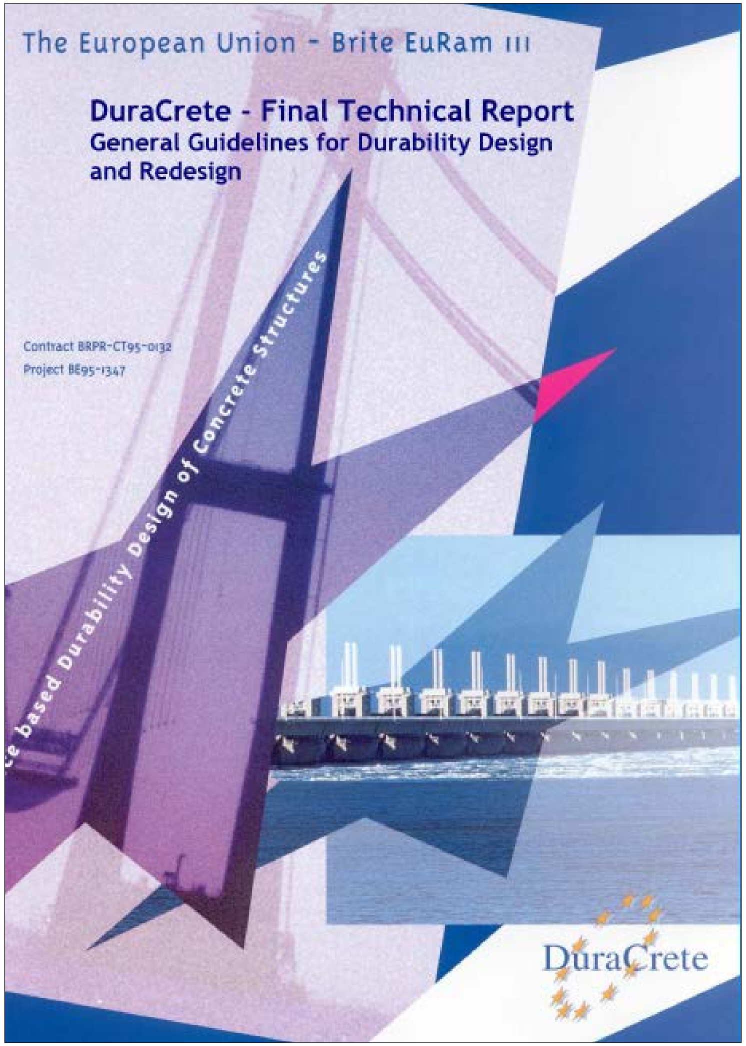
ACI 365.1R-00 became effective January 10, 2000.



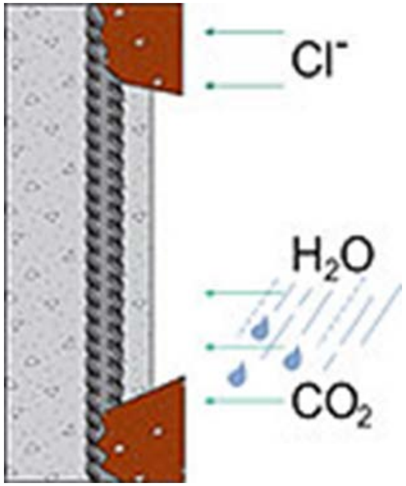
Common Deterioration Types

- Reinforcing steel corrosion
- Concrete cracking, spalling, delamination

- Structural steel corrosion following breakdown of protective coating systems

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)



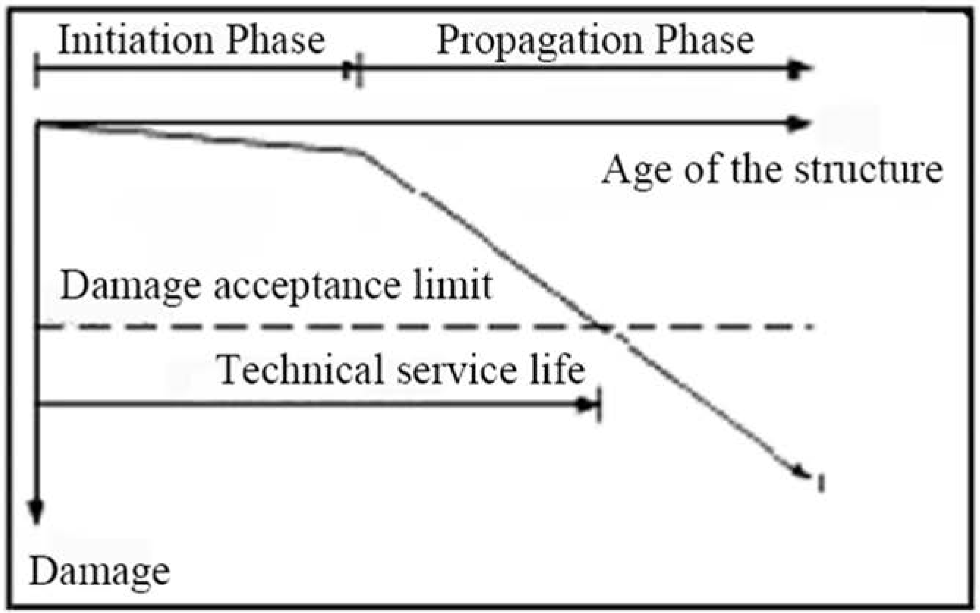
Material Resistance

- 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

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

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

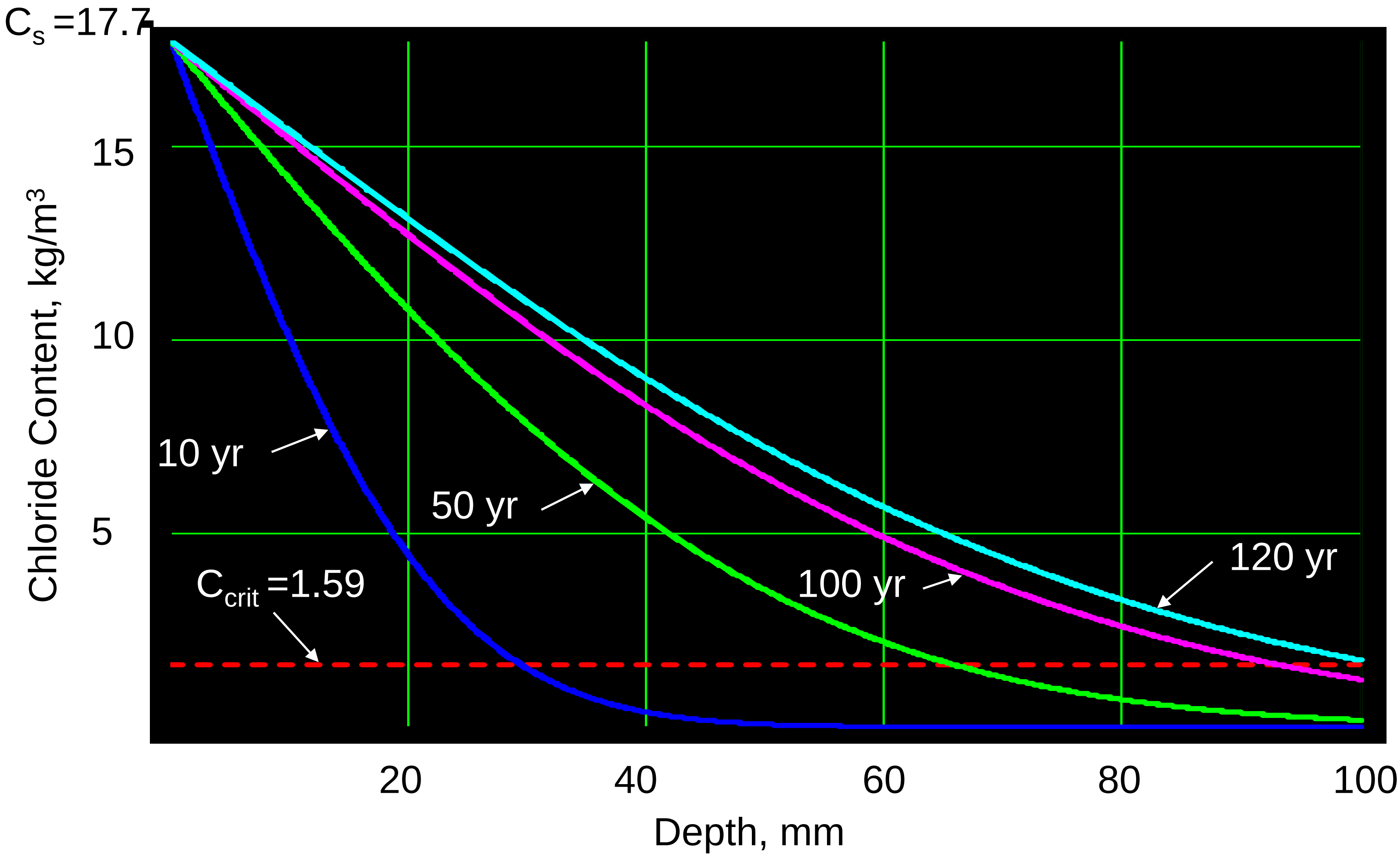
$$k_e = \exp\left(b_e\left(\frac{1}{T_{ref}} + \frac{1}{\mathbf{T_{real}}}\right)\right)$$

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

- **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



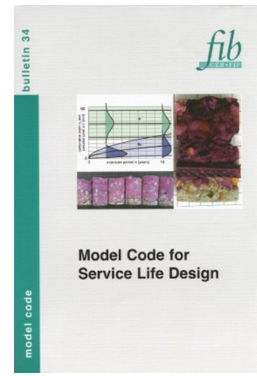
Current Specifications

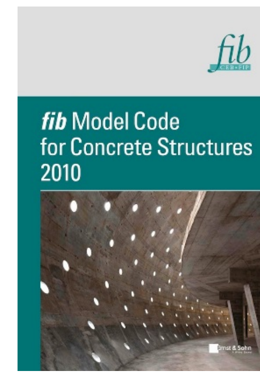
- *fib* Bulletin 34 – Model Code for Service Life Design (2006)

- *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

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

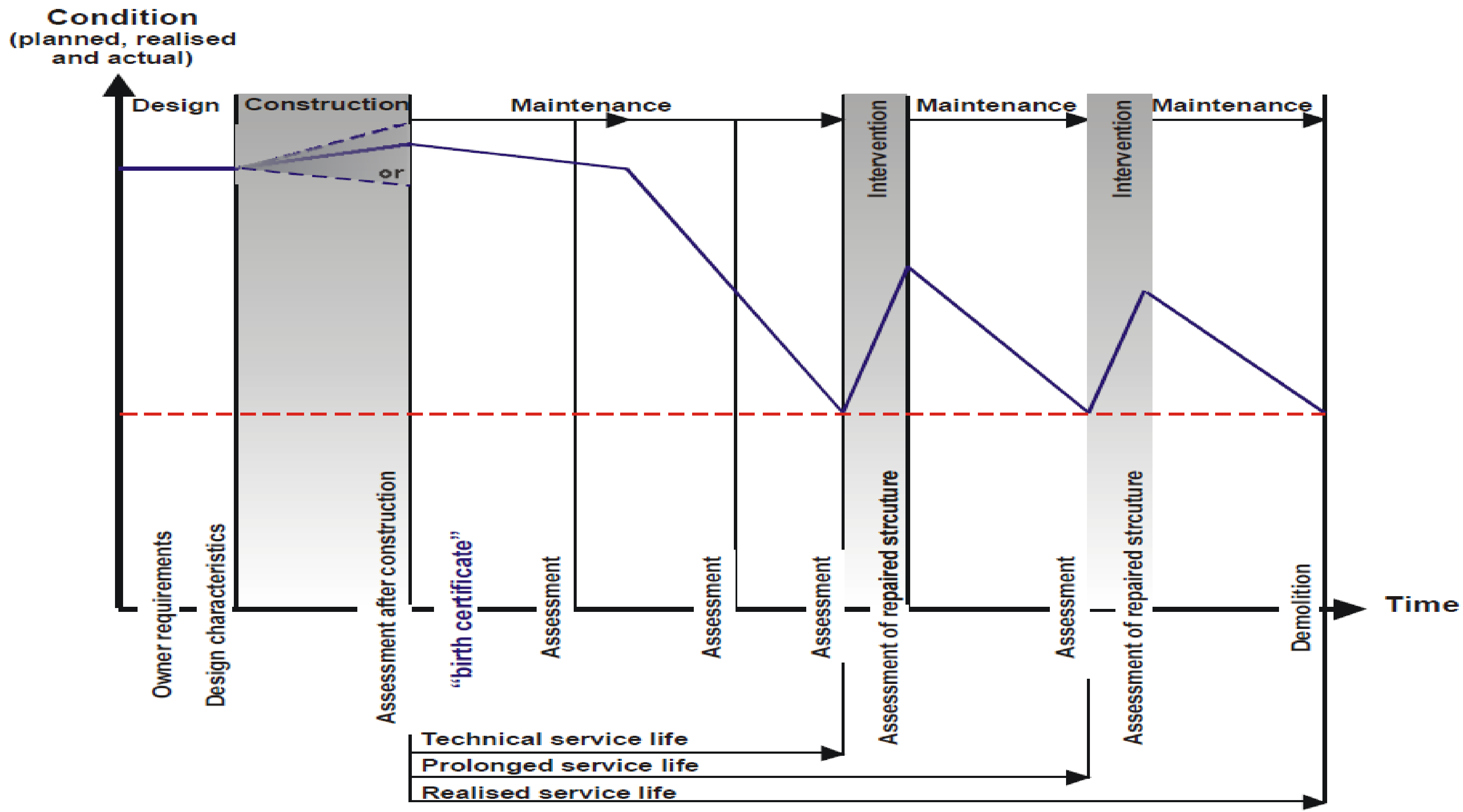


Fig. 2-1: Complete service life from birth to death, adapted from [28]

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 & 5.12
- 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 ≤ 0.4 ……………………………………….. 0.8
    - For W/C ≥ 0.5 ……………………………………….. 1.2

AASHTO LRFD Provisions

- Specified concrete cover dimensions

SECTION 5: CONCRETE STRUCTURES

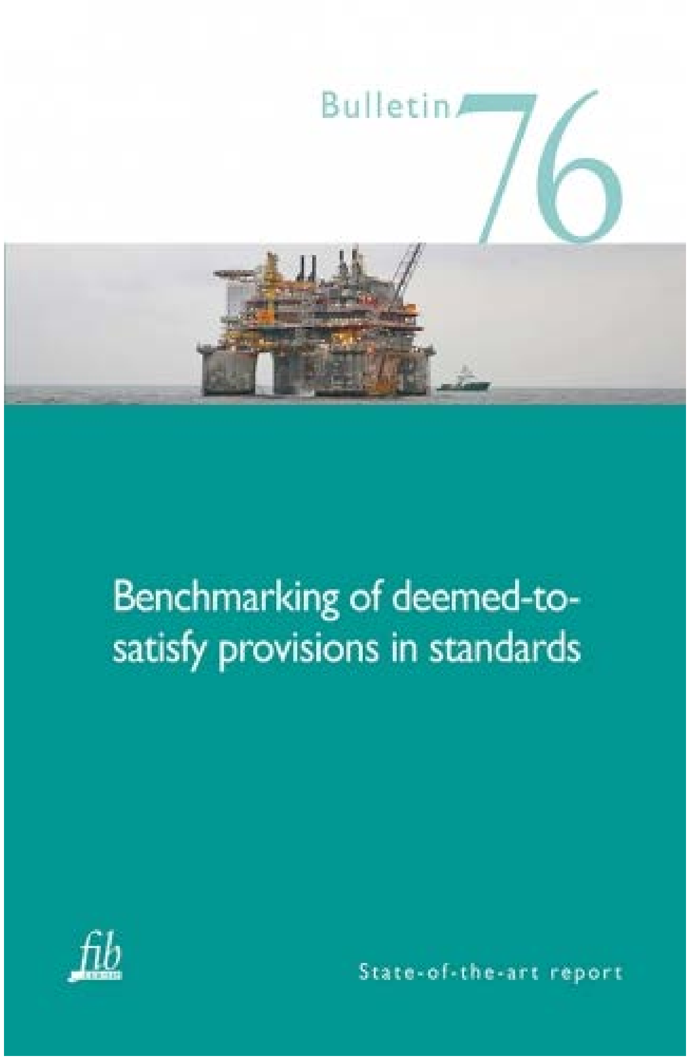
Table 5.12.3-1—Cover for Unprotected Main Reinforcing Steel (in.)

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

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)
0.007%	100%	3.8	Eurocode EN 1990 (ultimate limit state calibrated for a 50 year design life)
50%	50%	0.0	
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

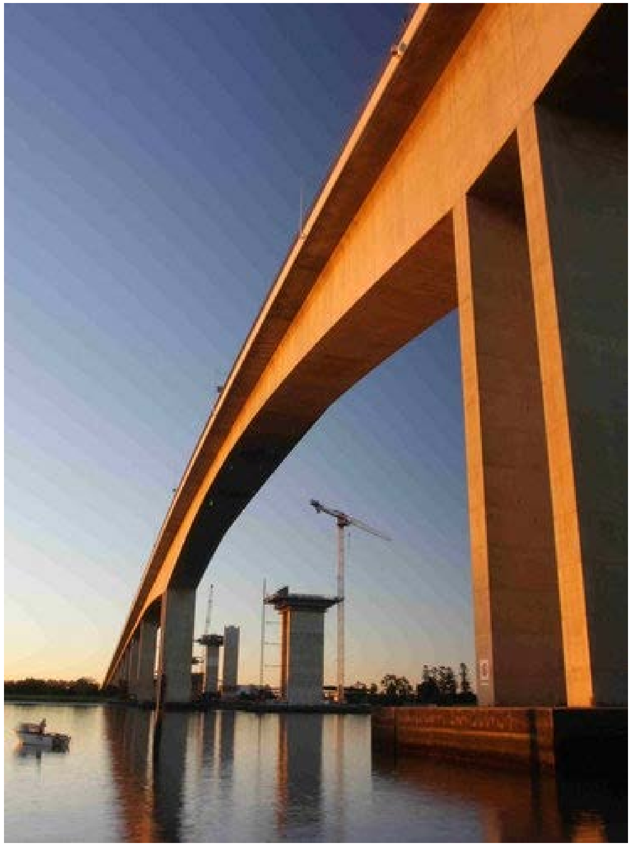
- Confederation Bridge, Canada –1997 (100 years)

Service Life Designed Structures

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

Service Life Designed Structures

- Gateway Bridge, Brisbane – 2010 (300 years)



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

SHRP2 R19A Team

RESEARCH – **TRB**

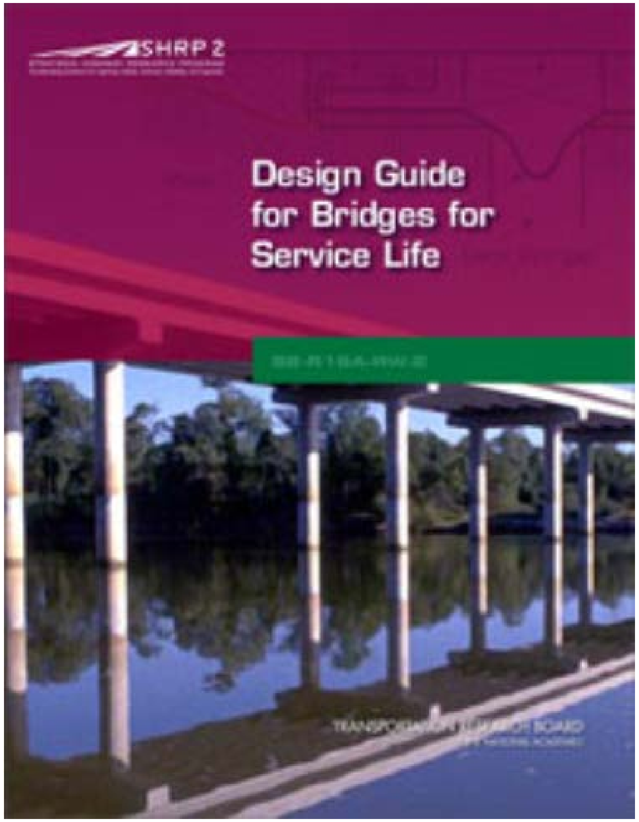
IMPLEMENTATION – **FHWA/AASHTO**

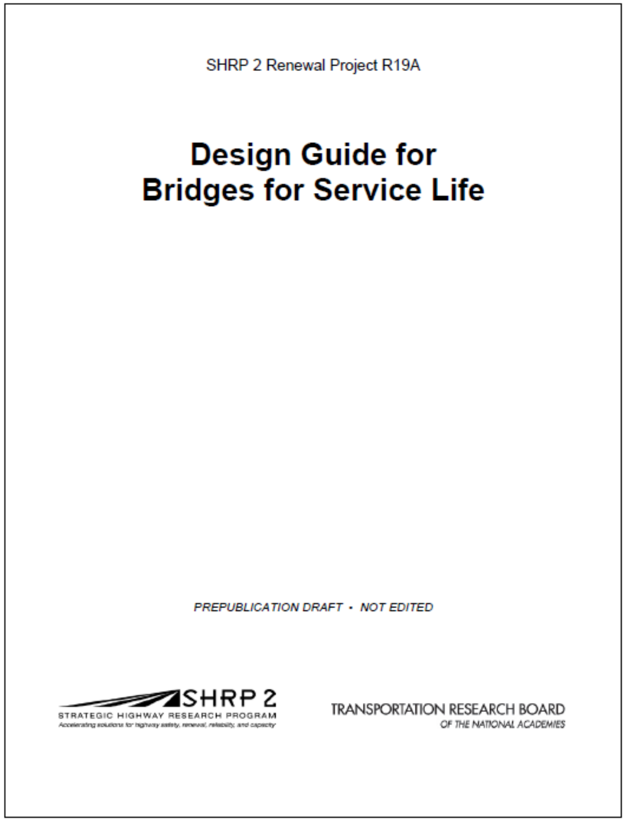
SUBJECT MATTER EXPERTS /
LOGISTICS SME LEAD – **CH2M**
TECHNICAL SMEs –
COWI

LEAD ADOPTER AGENCIES

Research Work Completed

- Project R19A – Service Life Design Guide

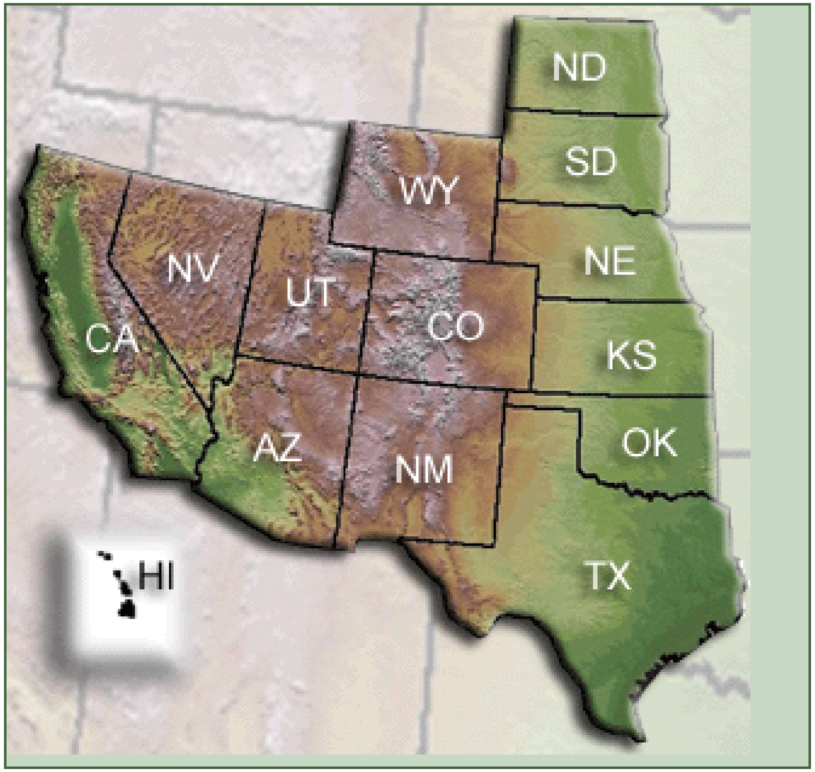




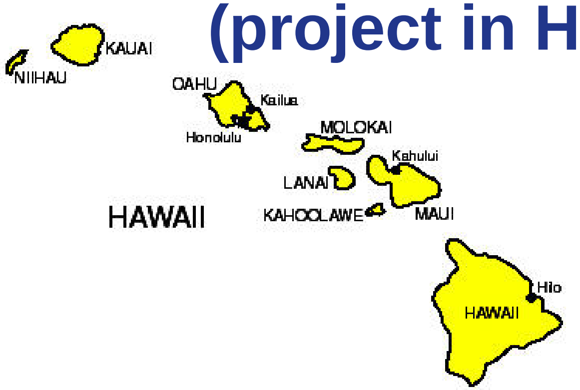
  - http://www.trb.org/Main/Blurbs/168760.aspx

IAP Lead Adopter Agencies

Oregon



Central Federal Lands (project in Hawaii)



IAP Lead Adopter Agencies

Iowa

Pennsylvania

Virginia

R19A IAP Funding

- State Agencies were awarded $150,000 each as Lead Adopters

- FHWA CFL was awarded $75,000

- Funding for technical assistance from the SME team is through SHRP2, and <u>NOT</u> part of agency awards

SHRP2 R19A Implementation Assistance Program Goals

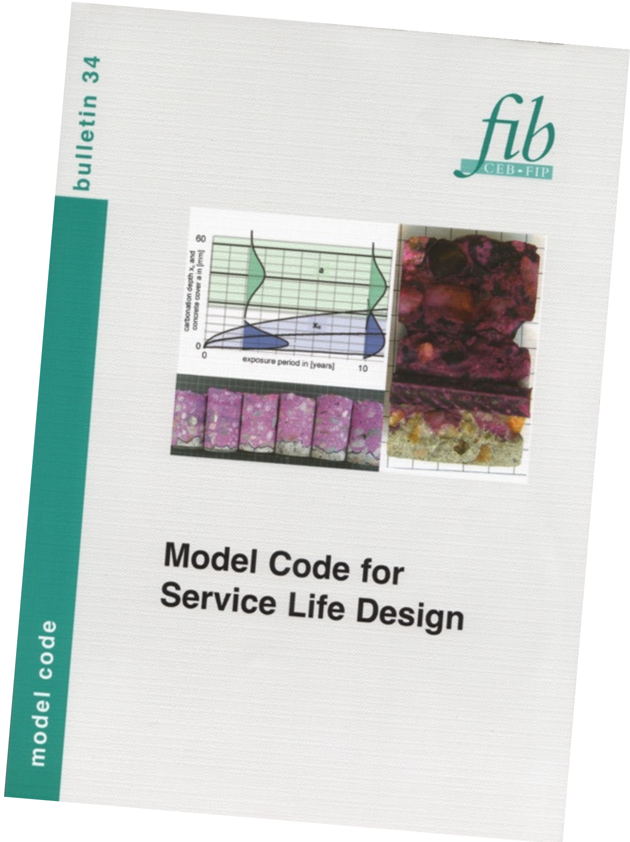
- Promote Service Life Design concepts
  - Marketing, outreach & training
  - Target 15% of state DOTs by 2016
- Produce basic elements for inclusion in an AASHTO Service Life Design Guide
  - Coordinate with SCOBS and T-9
- Build a strong technical foundation
  - Develop training & reference materials
  - Lessons learned summaries

Current Work Focus Areas

- Tests for durability design of new bridges and deck preservation of existing bridges
  - Testing concrete cores to evaluate chloride loading from de-icing chemicals and sea water
  - Concrete diffusion (permeability) properties
  - Measurement of as-constructed concrete cover
- Development of Service Life Design specification language for Requests for Proposals

Design Standard

- International Federation of Structural Concrete
- *fib* Bulletin 34 – Model Code for Service Life Design (2006)
  - Establishes design procedures
    - To resist deterioration
    - From environmental actions



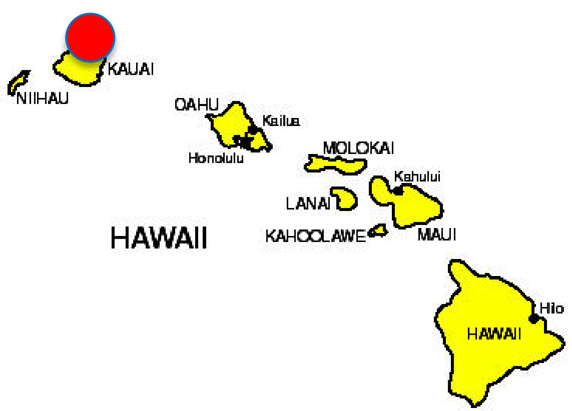
IAP Projects

IAP Team Leaders

- 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, Michael Brown

FHWA Central Federal Lands

- **Tropical Coastal Exposure on North Shore, Island of Kauai, HI**
  - Three bridge replacements on Highway 560 over Wainiha Stream
  - 500’ to 1,000’ from the coastline in remote setting
  - Single lane, 14’ wide roadway



FHWA Central Federal Lands

FHWA Central Federal Lands

- **Tropical Coastal Exposure on North Shore, Island of Kauai, HI**
  - Initial water samples taken for salinity measurements showed low chloride content
  - Additional samples to be taken at different times of year and at high and low tide
  - NT Build 492 tests will be performed on baseline concrete mix designs and will be contracted through the University of Hawaii during the design process
  - Coring of existing abutments at water line / splash zone for surface chloride concentration will be performed under the construction contract permits

Iowa DOT

- **New Bridge at Site with Extreme De-Icing Chemical Spray Exposure**
  - Woodbury County Highway K-25 over I-29 in western Iowa

  - 403’ Long by 43’-2” Wide 4-Span Continuous Steel Plate Girder Bridge
  - Using A1010 High Chromium Structural Steel for two girder lines along with A709 Grade 50W for the remaining four girder lines
  - Lab and field testing of the A1010 steel for structural and corrosion resistance performance
  - Industry Workshop – March 18, 2015
  - Currently under construction, fabrication nearly complete

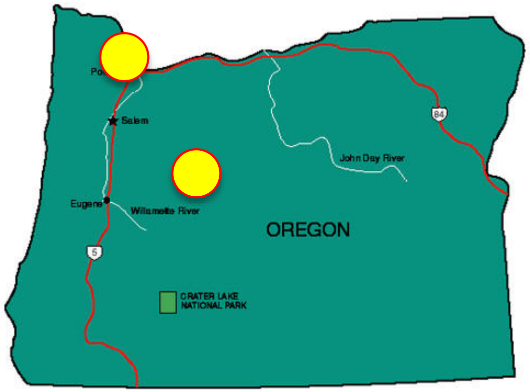
Iowa DOT

- **Replace Twin Structures on I-35 over South Skunk River near Ames**
  - Performed chloride profile testing to determine chloride loading (6 cores from existing structures, 126 cores from 19 bridges on 2 route corridors)
  - Performed NT Build 492 tests on representative concrete mix designs to evaluate expected deck/railing service life

  - Southbound structure – Under construction
  - Designed using current Iowa DOT policies
  - Northbound structure – Scheduled for January 2018 Letting
  - Will be designed using proposed methodology for deterioration from the environmental loading
  - Report on direct comparison between the two structures

Oregon DOT

- **I-5 Columbia River Crossing Design/Build – Portland to Vancouver**
  - Evaluate/modify RFP requirements for contractor to design/document to a 100-year service life
- **Replacement Bridge over Ochoco Creek in Prineville**
  - Single 66’ span by 65’-8” wide w/ precast spread box beams
  - Performing chloride profile testing to determine chloride loading (4 cores from existing structure)
  - Performing NT Build 492 tests on representative concrete mix designs to evaluate expected deck service life
  - Evaluating expected service life



Oregon DOT

- **Bridge Deck Evaluation in Various Chloride Exposure Zones**
  - Performed chloride profile testing to determine chloride loading (42 cores from 12 existing structures)
  - Additional structures scheduled to be tested through end of year
  - Categorization of chloride loading by geographic/climatic zones (Pacific Coast, \ ... ns and east)

Pennsylvania DOT

- **Statewide Evaluation of Chloride Resistance of Concrete**
  - Contracted with Lehigh University to perform NT Build 492 chloride migration coefficient tests on 105 samples from mix designs produced by 7 ready mix and 2 precast concrete suppliers in the state

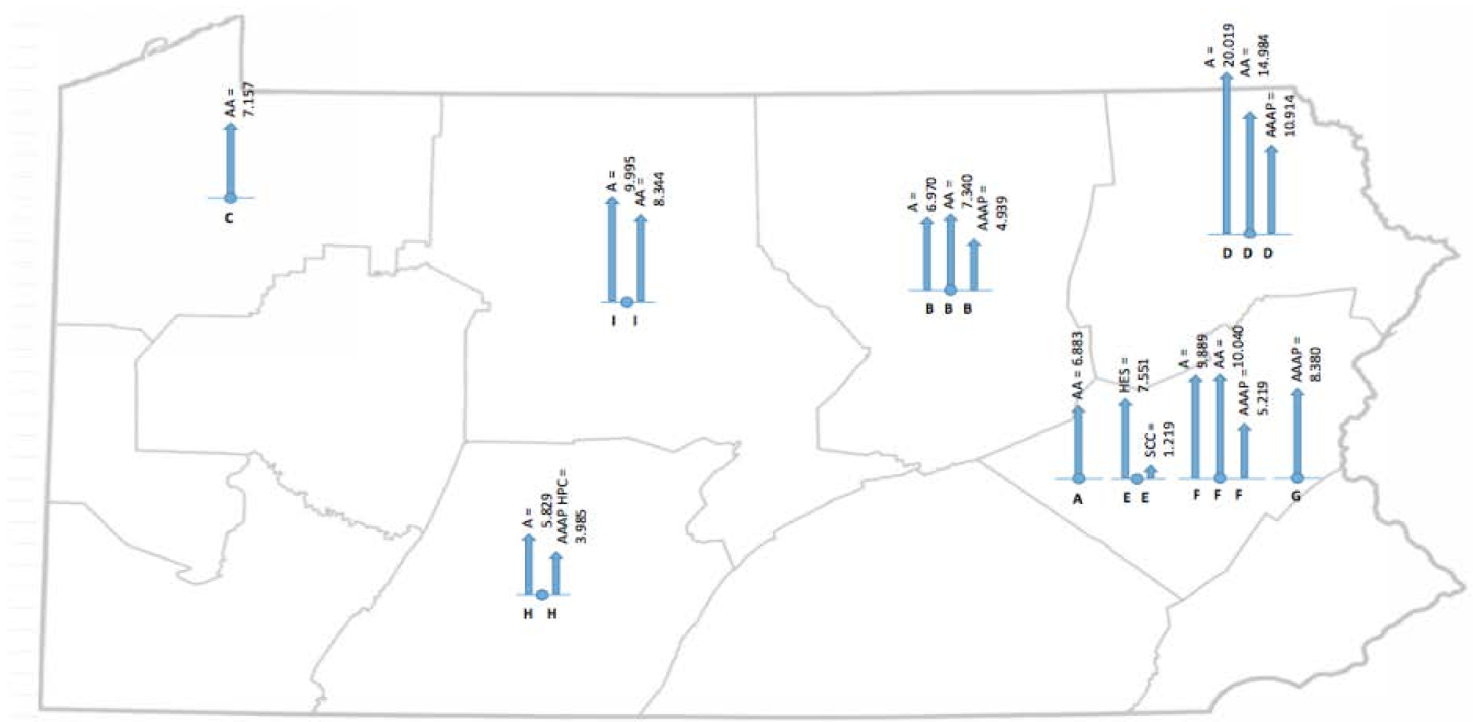


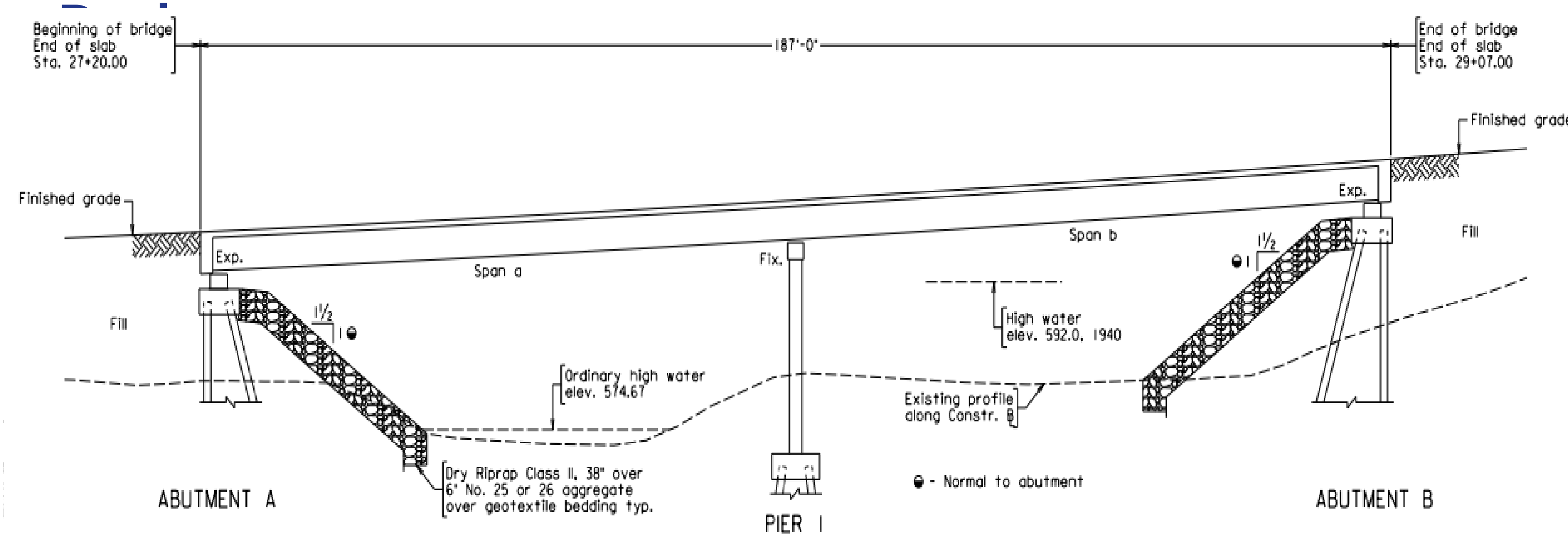
Figure 1: Company location map relative to PennDOT districts

Pennsylvania DOT

- **Statewide Evaluation of Chloride Resistance of Concrete**
  - Tests included standard, high performance (HPC) and self consolidating (SCC) concrete mixes
  - Tests were performed at 28, 56, and 112 days to evaluate effects of age
  - Performed evaluation of chloride migration coefficient versus concrete mix type, age, w/c ratio, unit weight, slump, and strength
  - Developed a full probabilistic assessment tool based on the fib Bulletin 34 methodology, and evaluated PennDOT certified mixes for a 100 year life
  - Initial indications are that most standard mix designs would not satisfy a 100 year life in a salt splash/spray zone

Virginia DOT

- **Model Corrosion Service Life of a Typical Virginia Bridge**



Service Environment

- Air Temperature
- Surface Chloride Concentration, C_s

Concrete Mix Properties

- Concrete Initial Chloride Concentration, $C_{(x,t=0)}$
- Chloride Migration Coefficient, D

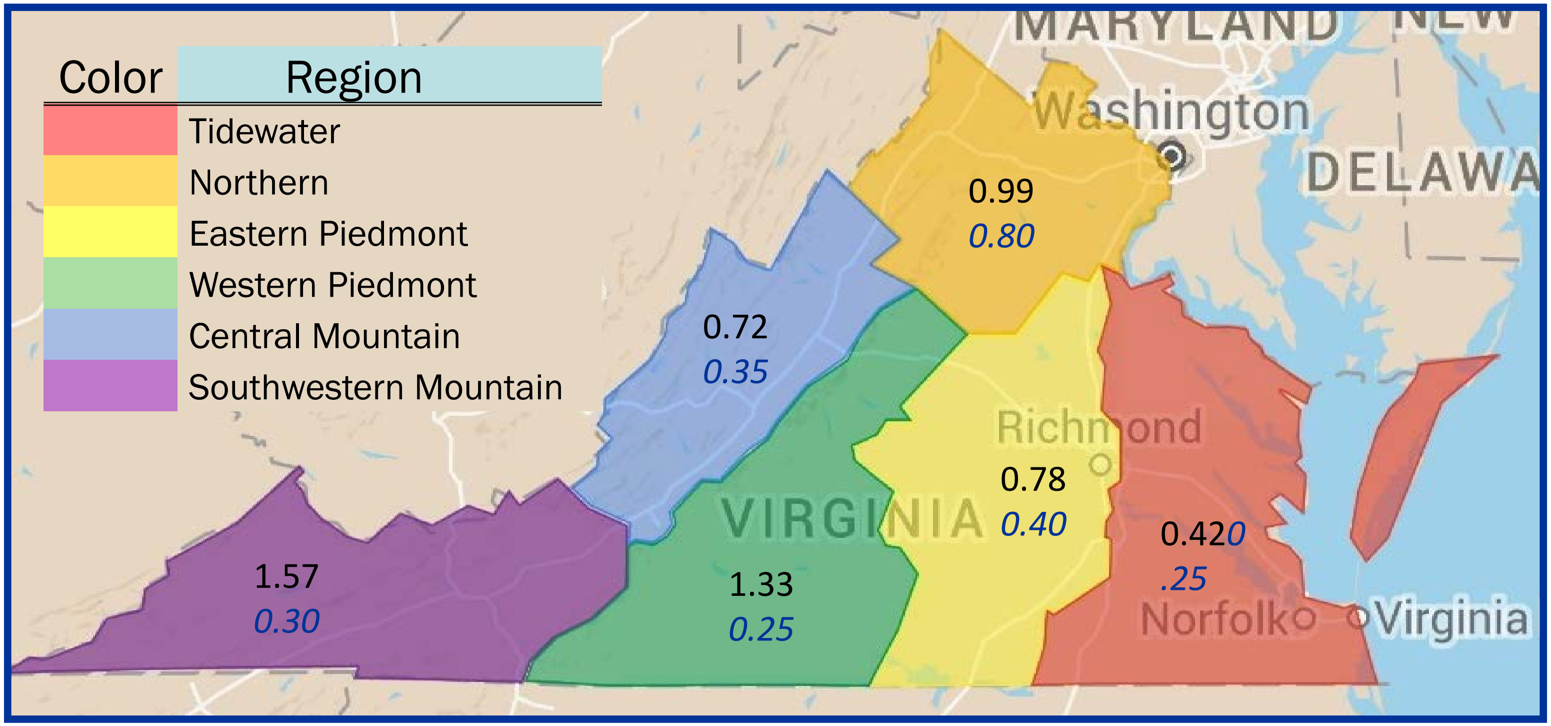
Virginia DOT

Virginia’s Goals:

- Consider proposed methods to model for service life design
- Demonstrate how models can be used to support decision-making in design
- Develop a database of reference values specific to Virginia for use in modeling

Virginia DOT

- **Evaluation of Chloride Surface Concentration from De-Icing**
  - Categorization of chloride loading by zones



  - Historical data (Williamson, 2007)
  - *fib 34-predicted*

$$\left(\% \frac{mass\ Cl^{-}}{mass\ binder}\right)$$

Virginia DOT

- **Evaluation of Chloride Diffusion Properties of Statewide Concrete Mix Designs**
  - Typical Deck mix (A4) – 4,000 psi HPC
    - All Virginia DOT concrete mixes contain mineral admixtures to reduce permeability
  - Variety of source materials statewide
  - New low-cracking concrete specification
  - NT Build 492 tests performed on 9 current bridge construction projects (8 additional bridges to be tested later this year)
  - Developed a full-probabilistic analysis tool for evaluation of data

IAP Next Steps

- Conduct Agency Training Workshops
- Develop Reference Material Documentation
- Round 7 Implementation Assistance
  - $500,000 in Lead Adopter awards made available
  - 2 awards for $100,000 each:
    - Iowa DOT
    - Maine DOT

Future Research

- AASHTO T-9 – Bridge Preservation Technical Committee sponsoring NCHRP Research Project 12-108 (Pending)
- Uniform Service Life Design Guide Specification
  - Conduct Literature Review
  - Synthesize Gaps in Current Practice
  - Develop a Methodology considering:
    - Multiple Analysis Methods
    - Deterioration Processes and Exposure Zones and Loads
    - Service Life Target Based on Functional Requirements
    - Selection of Alternative Designs to Achieve Target Service Life
    - Evaluate Effectiveness of Design, Construction, Inspection Strategies and Management Practices
  - Produce Report and Guide Specification

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, OR, PA, VA)
- AASHTO T-9 Initiated Research
  - NCHRP 12-108 Uniform Service Life Design Guide

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