Western Bridge Engineers Seminar - September 9, 2015 - Reno, NV

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DURABILITY DESIGN OF BRIDGES FOR SPECIFIED SERVICE LIFE

Presentation Overview

- Durability / 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?

How Long Will Your Bridge Last?
- The Need to Predict Service Life of Bridge Components

Mike Bartholomew/CH2M HILL

Western Bridge Engineer's Seminar

Boise, Idaho

September 23-26, 2007

Service Life Background

- Bridge Design has historically focused primarily on structural engineering aspects
  - Selecting materials by their strength properties (f'c, fy) and sizing components to resist 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 because the material components have begun to deteriorate
    - Not from unanticipated loads
    - But by loss of function from steel corrosion and concrete cracking/spalling, as a result of the environmental exposure conditions

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

Service Life Design (SLD)

- Design approach to resist Deterioration caused by Environmental Actions
  - Also called Durability Design & often Design for 100-year Service Life
- Similar to design against Structural Failure caused by External Loads
  - What we know as Strength Design

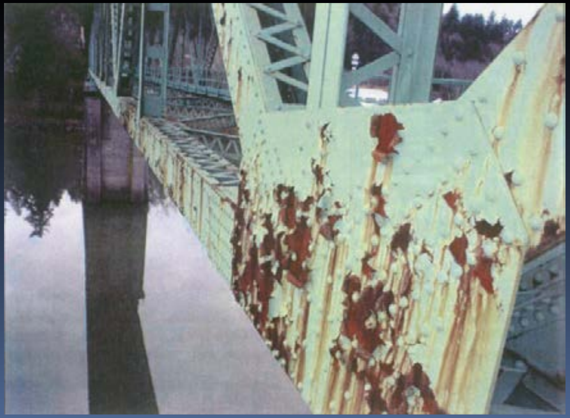
Service Life Design Principles

- 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

Deterioration

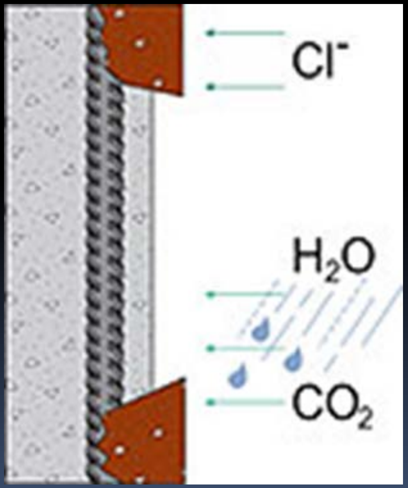
- Types of Deterioration
  - Reinforcing Steel Corrosion
  - Concrete Cracking, Spalling, Delamination

  - 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
- Freeze/Thaw Cycles
- Alkali-Silica Reaction (ASR)
- Abrasion (ice action on piers, studded tires on decks)



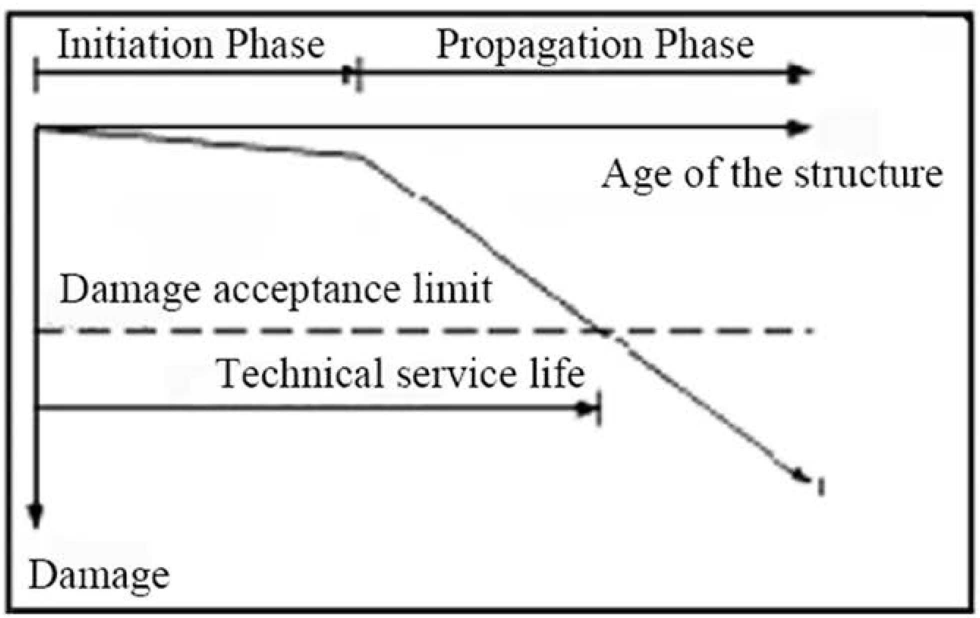
Material Resistance

- 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

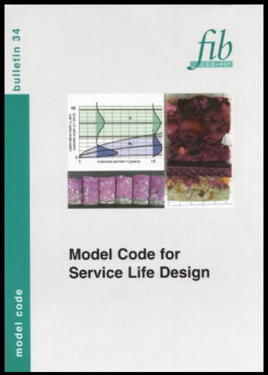
- Reinforcing Steel Corrosion is Defined with a Two-Phase Deterioration Model
  - Initiation – No Visible Damage is Observed
  - Propagation – Corrosion Begins and Progresses



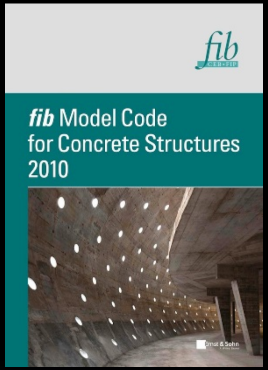
Service life of concrete structures. A two-phase modelling of deterioration. [Tuutti model (1982)]

Current Specifications for Service Life Design

- *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)


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

- All focus on Concrete Structures only, little available for Steel

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)
- Not always the most cost effective solution

Deemed to Satisfy Method

- Prescriptive approach used in most major design codes
  - e.g., In severe environment, use concrete with f'c=5000 psi, 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 [illegible]	Dissolved [illegible]
[illegible] permeability	[illegible] required		[illegible] 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	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

Chloride Ingress Model

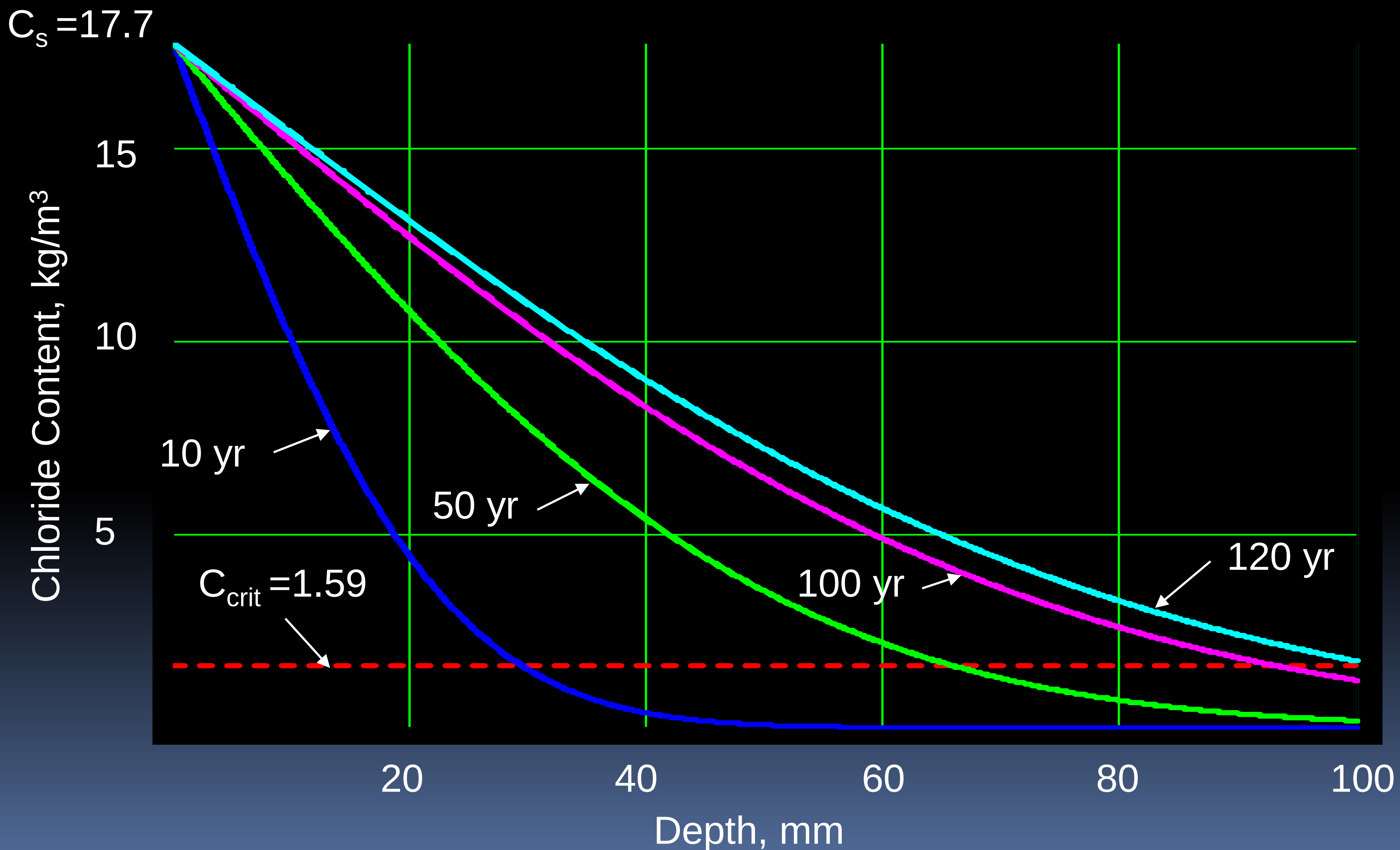
- Fick's 2nd Law Models Time to Initiate Corrosion in Uncracked Concrete (Cracks < 0.3 mm or 0.012")

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

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 vs. Age

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



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

Full Probabilistic Method

fib Bulletin 34, Section B2 - Full probabilistic design method for chloride induced corrosion - uncracked concrete

Fick's 2nd Law

$$C_{crit} = C(x = a, t) = C_o + (C_{s,\Delta x} - C_o)\left[1 - \mathrm{erf}\left(\frac{a - \Delta x}{2\sqrt{D_{app,C} \cdot t}}\right)\right]$$ Equation (B2.1-1)

$$D_{app,C} = k_e D_{RCM,0} k_t A(t)$$ Equation (B2.1-2)

$$k_e = \exp\left(b_e\left(\frac{1}{T_{ref}} + \frac{1}{T_{real}}\right)\right)$$ Equation (B2.1-3)

$$A(t) = \left(\frac{t_o}{t}\right)^{\alpha}$$ Equation (B2.1-4)

Parameter	Description	Units	Distribution Function	Normal Distr Coefficients: Mean, μ	Std Dev, σ	Coeff of Variation, σ/μ
$D_{RCM,0}$	Chloride Migration Coefficient (from Nordtest NT Build 492 results)	m^2/sec	Normal	8.90E-12	1.78E-12	0.20
		mm^2/yr		280.9	56.2	
		in^2/yr		0.435	0.087	

Trial	$D_{RCM,0}$ (mm^2/yr): rand 0-1	RESULT
1	0.202	233.97
2	0.538	286.23
3	0.907	355.22
4	0.372	262.51
5	0.111	212.23
6	0.004	131.77
7	0.152	223.01
8	0.312	253.25
9	0.790	326.21
10	0.514	282.85
11	0.371	262.37
12	0.499	280.75
13	0.706	311.24
14	0.843	337.45
15	0.646	301.87

Service Life Designed Structures

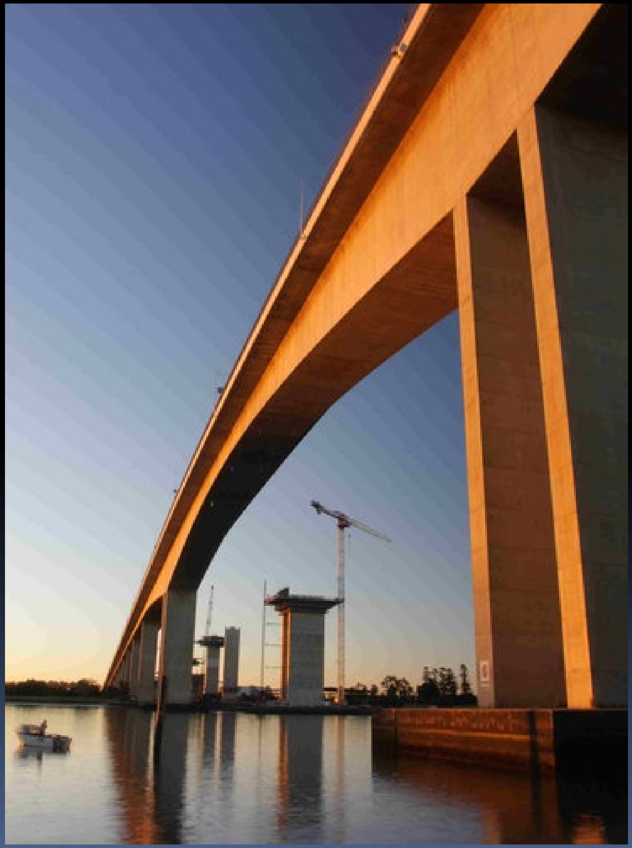
- Confederation Bridge, Canada –1997 (100 years)

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)

Need More Focus on These

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

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 Design Steps

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

New Contract Requirements

- Identify Additional Tests and Data Collection Requirements
  - Concrete Chloride Migration Coefficient
  - 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 Chloride Migration Coefficient – Short Term Tests
  - **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)
  - ~~**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)~~

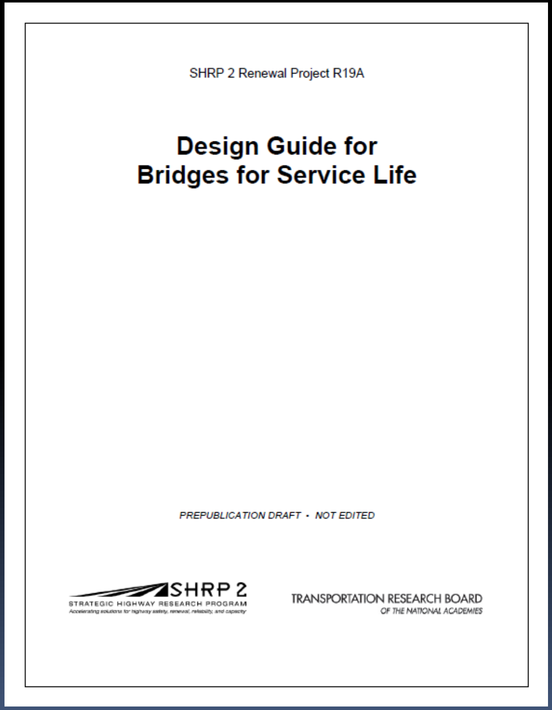
Construction Test Requirements

- 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

What's Currently Being Done

- Strategic Highway Research Program 2
  - 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

SHRP2 R19A Team

RESEARCH –
TRB

IMPLEMENTATION –
FHWA/AASHTO

SUBJECT MATTER EXPERTS / LOGISTICS SME LEAD –
CH2M

TECHNICAL SME's –
Buckland and Taylor

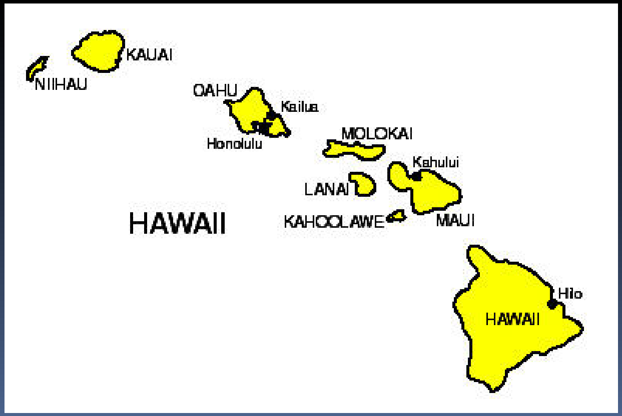
SHRP2 R19A Implementation Assistance Program Goals

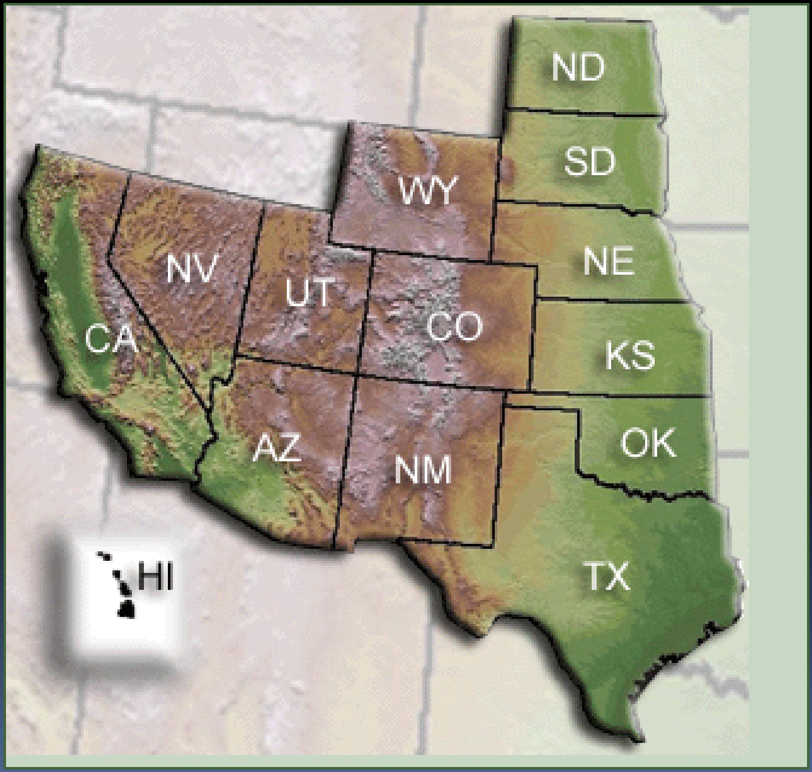
- Promote Service Life Design Concepts
  - Marketing, Outreach & Training
  - Target 15% of State DOTs by 2016
- Produce Basic Elements for Inclusion in an AASHTO Service Life Design Guide
  - Coordinate with SCOBS and T-9
- Build a Strong Technical Foundation
  - Develop Training & Reference Materials
  - Lessons Learned Summaries

Who Are the Lead Agencies?

Oregon

Central Federal Lands (project in Hawaii)

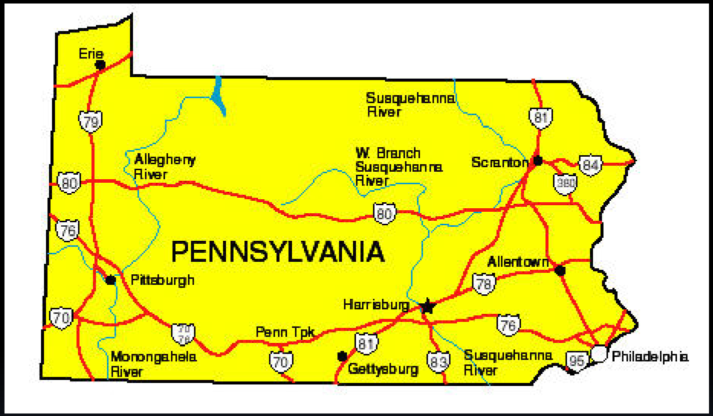




Who Are the Lead Agencies?

Iowa

Pennsylvania



Virginia

R19A IAP Funding

- State Agencies were awarded Lead Adopter grants of $150,000
- FHWA CFL was awarded $75,000
- Funding for technical assistance from the SME team is through SHRP2, and NOT part of agency grants

R19A Next Steps

- Look for tools from the Implementation Program

- Next Round of Implementation Assistance
  - User Incentive Offering in Round 7 in early 2016
  - Instructions for application on the GO SHRP2 website

http://www.fhwa.dot.gov/goshrp2/ImplementationAssistance

Look for instructions and applications at the SHRP2 website
- User Incentives / Training

Future Research

- AASHTO T-9 – Bridge Preservation Technical Committee sponsoring NCHRP Research Project to Develop
- Uniform Service Life Design Guide Specification
  - Quantify Environmental Exposures
  - Define Deterioration Models for Steel Bridges and Coatings
  - Adopt Construction Testing Specifications
  - Develop Life-Cycle Costing Tools
  - Recommend In-Service Maintenance & Inspection Procedures
  - Assess Remaining Life of Existing Structures
- RFP Due Out in Next 2 Months

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 Uniform Service Life Design Guide

- Thank you for your attention

- Mike Bartholomew

ch2m

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