WARDROP

Manitoba Floodway Expansion Authority

Long Term Durability and Life Cycle Cost Analysis of Steel-Free Bridge Deck Slabs

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Presentation Outline

- Introduction
- Part 1 - Durability of SFD and GFRP
  - Background
  - Results of Previous Research
  - ISIS Canada Research
  - Estimated Service Life
- Part 2 - Life Cycle Cost Analysis
  - Bridge Structure
  - Methodology
  - Service Life Predictions
  - Results
- Conclusions and Recommendations

Introduction

- Goal of presentation:
  - Define current State-of-the-Art on durability and long-term performance of Steel-Free Deck (SFD) with GFRP reinforcement
  - Compare cost-effectiveness of various deck systems to the SFD
    - Summary of results used for bridge deck study for the Red River Floodway Expansion Project

Part 1

State-of-the Art on Durability and Long-term Performance of SFD with GFRP reinforcement

History of Steel-Free Deck Slab (SFD)

- 1st Generation
  - Five bridges constructed between 1995 to 1998
  - All performing well

- 2nd Generation
  - 2004 - first bridge constructed in Manitoba
  - Crack control grid is effective

Durability of GFRP Reinforcement

- What happens to GFRP reinforcement embedded in an alkaline environment (i.e. concrete) under sustained loading?
- How long does it last?
- Can we see if there’s a problem on the surface of a concrete deck slab?

Results of Previous Research

- Critical factor
  - Properties of the protective resin coating
- Other factors
  - Type of matrix/resin (vinyl ester)
  - Type of fibres (E-glass)
  - Stress level
  - Type of environment for testing (e.g. maximum temperature, type of alkaline solution)

"Typically, results have indicated that GFRP reinforcement can be used efficiently as concrete reinforcement at stress levels under sustained factored loads of 30% of ultimate strength."

Dr. Benmokrane

ISIS Canada Research

- Field investigations:
  - No deterioration of GFRP reinforcement was evident
  - No chemical degradation of GFRP due to alkalinity of concrete
- Results of fatigue testing:
  - GFRP has best fatigue resistance
- Precast steel-free deck panels:
  - Actual stress levels at service load in GFRP reinforcement are less than 10% of ultimate strength based on experimental data and theoretical calculations

Estimated Service Life for GFRP Reinforcement

- Based upon field investigation, fatigue tests, experimental data and actual service stress levels in bridge deck slabs:

100 years

Part 2

Life Cycle Cost Analysis

Red River Floodway Expansion Project

Replacing six existing highway bridges with ten new bridge crossings

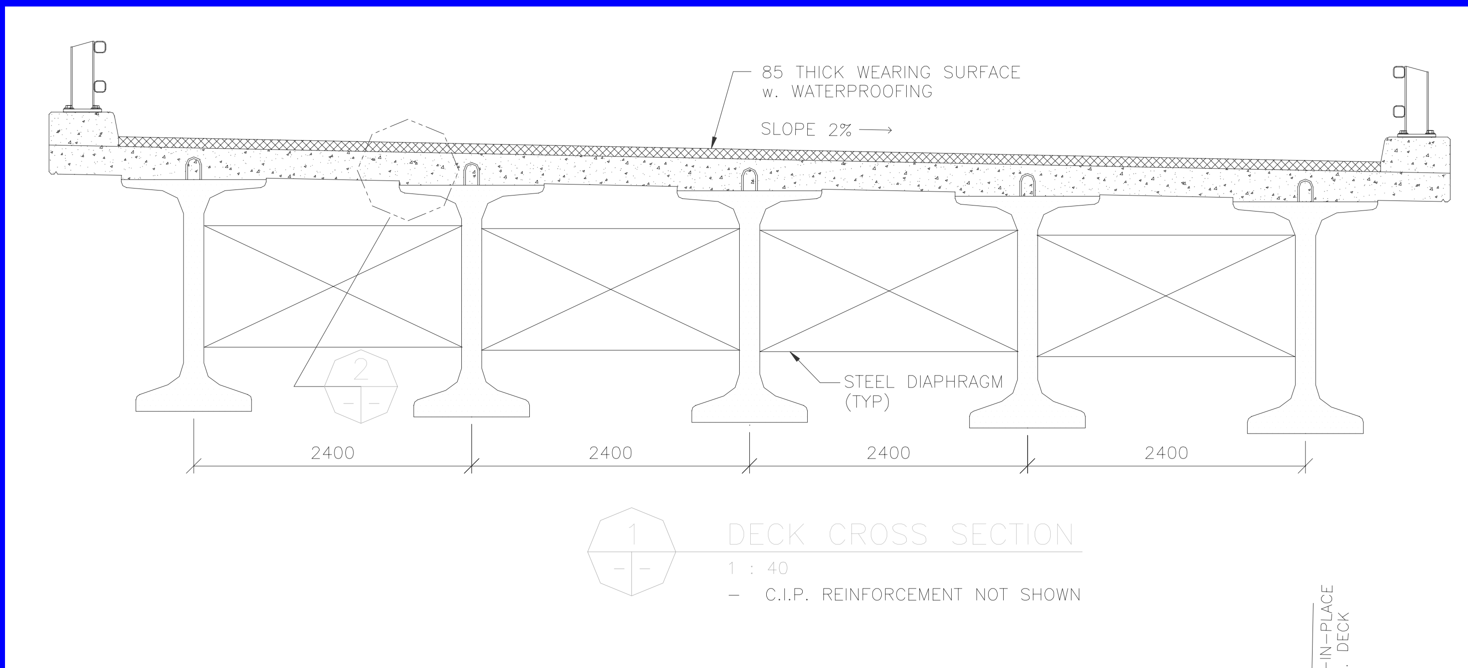
Budget Value of $160 Million over the next 4 years

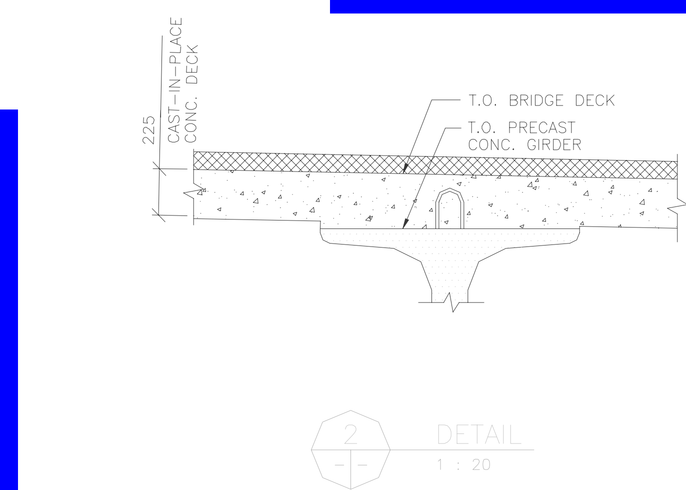
Goal of LCCA for Floodway Bridges

- Determine the most cost-effective deck system for the floodway highway bridges
- 75 design service life considering:
  - Anticipated initial capital cost
  - Realistic maintenance
  - Sensitivity of effective interest rates and typical maintenance costs for concrete repairs

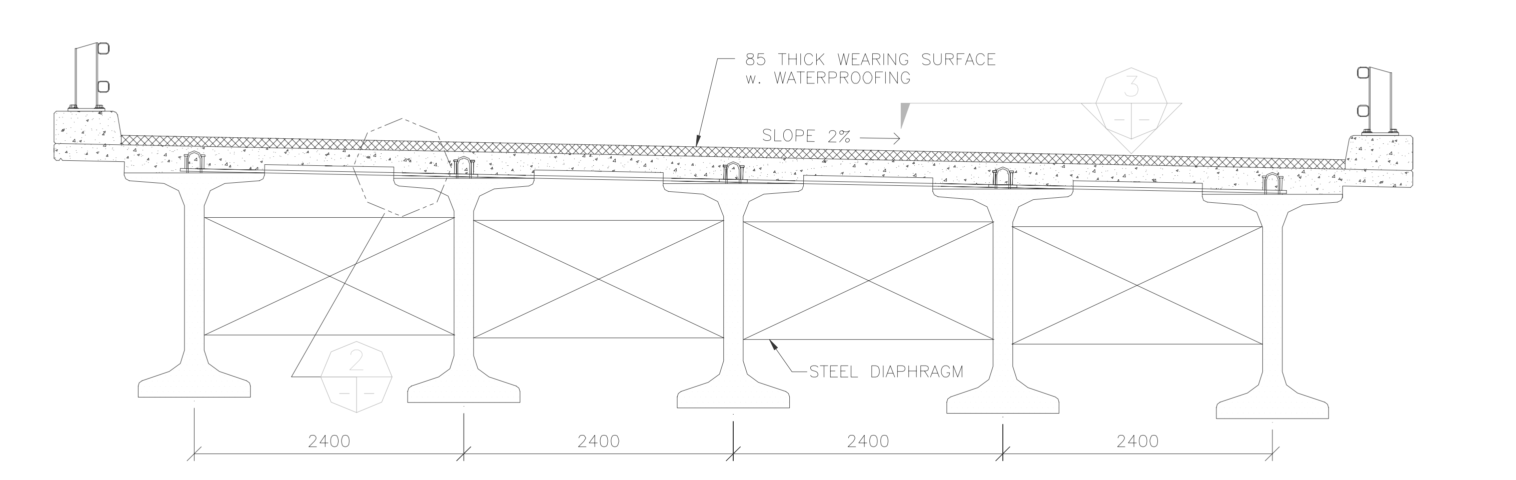
Typical Elevation Floodway Highway Bridge

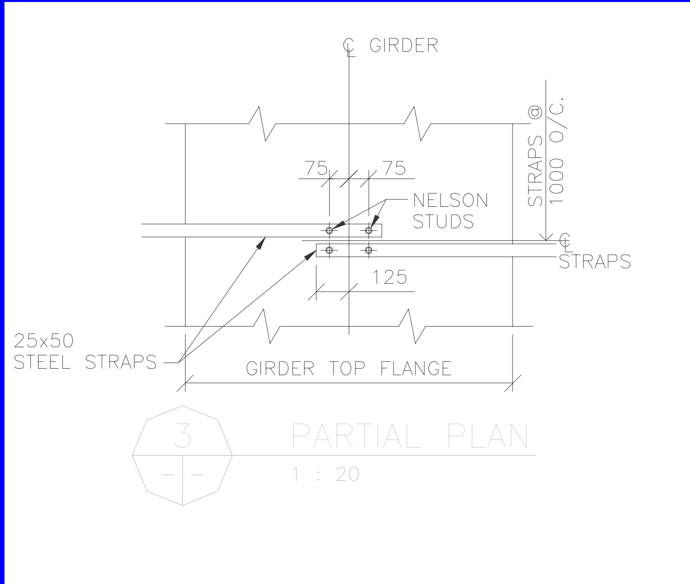
Cast-in-Place - Conventional Deck System

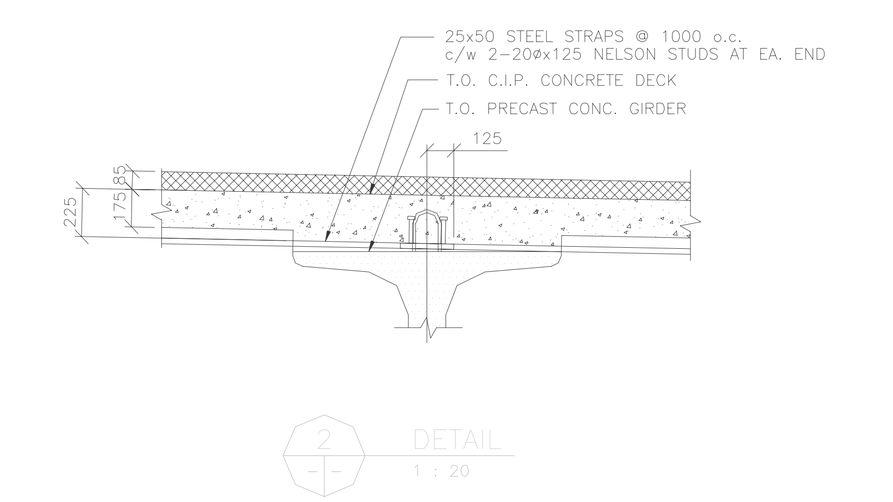




Cast-in-Place – Steel-Free Deck







Methodology

- Investigate potential deck systems
- Complete preliminary design
- Calculate material quantities
- Define deck protection systems
- Estimate initial construction costs
- Estimate service life for components
- Define maintenance scenarios
- Identify well-defined and variable parameters
- Perform NPV life cycle cost analysis
- Evaluate sensitivity of analysis to variable parameters

Investigate Potential Deck Systems

- Reinforcement, concrete, deck protection
- Literature review
- Examine past field experience and compare to corrosion prediction models
- MTGS, City of Winnipeg and MFA

Deck Systems Evaluated

Deck Number	Reinforcement (Top/Bottom)
1	Black/Black
2	Galvanized/Galvanized
3	Epoxy/Epoxy
4	MMFX/MMFX
5	Stainless Clad/Black
6	Solid Stainless/Black
7	GFRP/Black
8	GFRP/GFRP
9	Corrosion Resistant Deck (Black)
10	Corrosion Resistant Deck (Black)
11	Corrosion Resistant Deck (MMFX2)
12	Corrosion Resistant Deck (MMFX2/GFRP)
13	Corrosion Resistant Deck (/GFRP)
14	Corrosion Resistand Deck (GFRP/Black)

Complete Preliminary Design

- CHBDC Empirical Method
  - Conventionally reinforced deck slab systems
- Proposed Section 16 of CHBDC
  - steel-free deck slabs

Calculate Material Quantities

- Assumed empirical deck design approach
- GFRP based on strength design – negative moment regions
- Corrosion resistant deck based on current CHBDC revision - top reinforcement provided over piers and at deck overhangs

Define Deck Protection Systems

- 90 mm bituminous pavement overlay complete with a waterproof membrane and protection board
- Polymer overlay
- 50 mm thick high performance concrete overlay

Estimate Initial Construction Costs

- Supply and Installation of Reinforcement
- Supply and Placement of Concrete
- Supply and Installation of Steel Straps
- Supply and Installation of Overlay
- Miscellaneous Costs

Initial Supply Cost
Different Reinforcement Types

Initial Supply Cost ($/kg)					
Reinforcement Type					
GFRP	Black	MMFX2	Epoxy/ Galvanized	Solid SS316LN	SS Clad 316
$2.10	$1.35	$2.60	$2.10	$11.85	$7.20

Initial Supply Cost
GFRP vs. Black Steel

GFRP		Steel	
Bar Size	V-ROD (Pultrall)	Bar Size	Black
#3 (9M)	$1.40	10M	1.32
#4 (12M)	$2.26	10M	2.13
#5 (16M)	$3.32	15M	1.57
#6 (19M)	$4.83	20M	1.52
#8 (25M)	$8.10	25M	1.53

Service Life of Deck Alternatives

- Based on Performance of:
  - Reinforcement
  - Protection Method
  - Maintenance Cycles

Predicted from Chloride Diffusion Models:

Fick's Law and Life 365

Estimated Service Life Different Reinforcement Types

Reinforcement Type	Estimated Service Life*	Service Life Used*	
		Normal Strength Concrete (NC)	High Performance Concrete (HPC)
Black	20-25 NC 35-40 HPC	25	35
Galvanized	15-50 NC 35-70 HPC	30	40
Epoxy	20-50 NC 35-75 HPC	30	45
MMFX (Require 3-4x's Chloride Threshold as Black)	25-50 NC 45-75 HPC	35	50
Stainless Steel Clad 316	100+ NC/HPC	100	100
Solid Stainless Steel 316LN or Duplex 2205	100+ NC/HPC	100	100
GFRP	50-100 NC/HPC	100	100
Black in Bottom	40-50 NC 100+ HPC	40	60

Deck Protection Systems

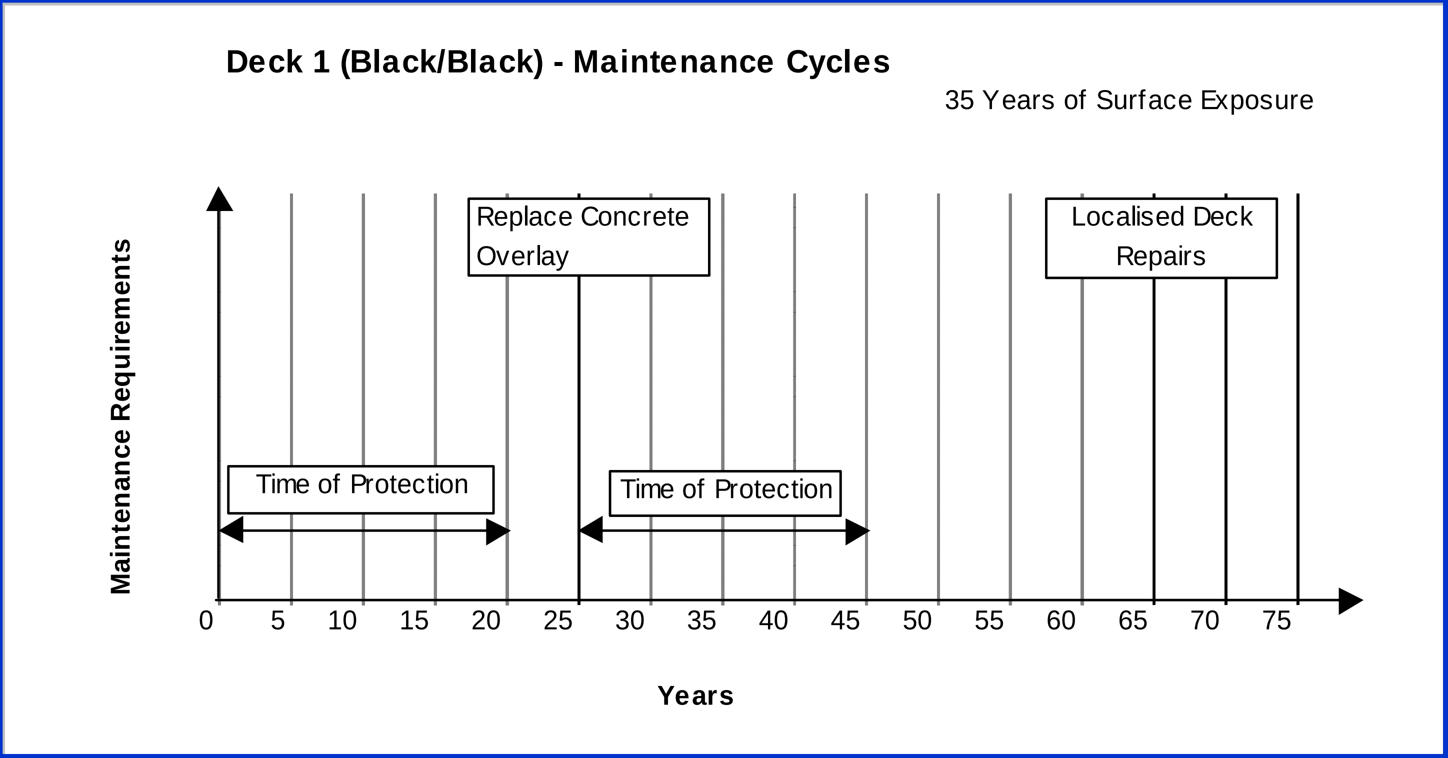
Protection Method	Years Providing Protection Against Chloride Diffusion	Replacement Timing (Years)
Waterproof Membrane (4 mm thick) with an Asphalt Overlay	20	25
Polymer Overlay	10	15
HPC 50 mm Overlay	20	25

Maintenance Cycles

- Based on time that upper surface of concrete deck can be exposed to chloride penetration
- Treated all systems equally based on their performance qualities
- Developed for each deck system
- Quantity of localised deck repair estimated for each deck

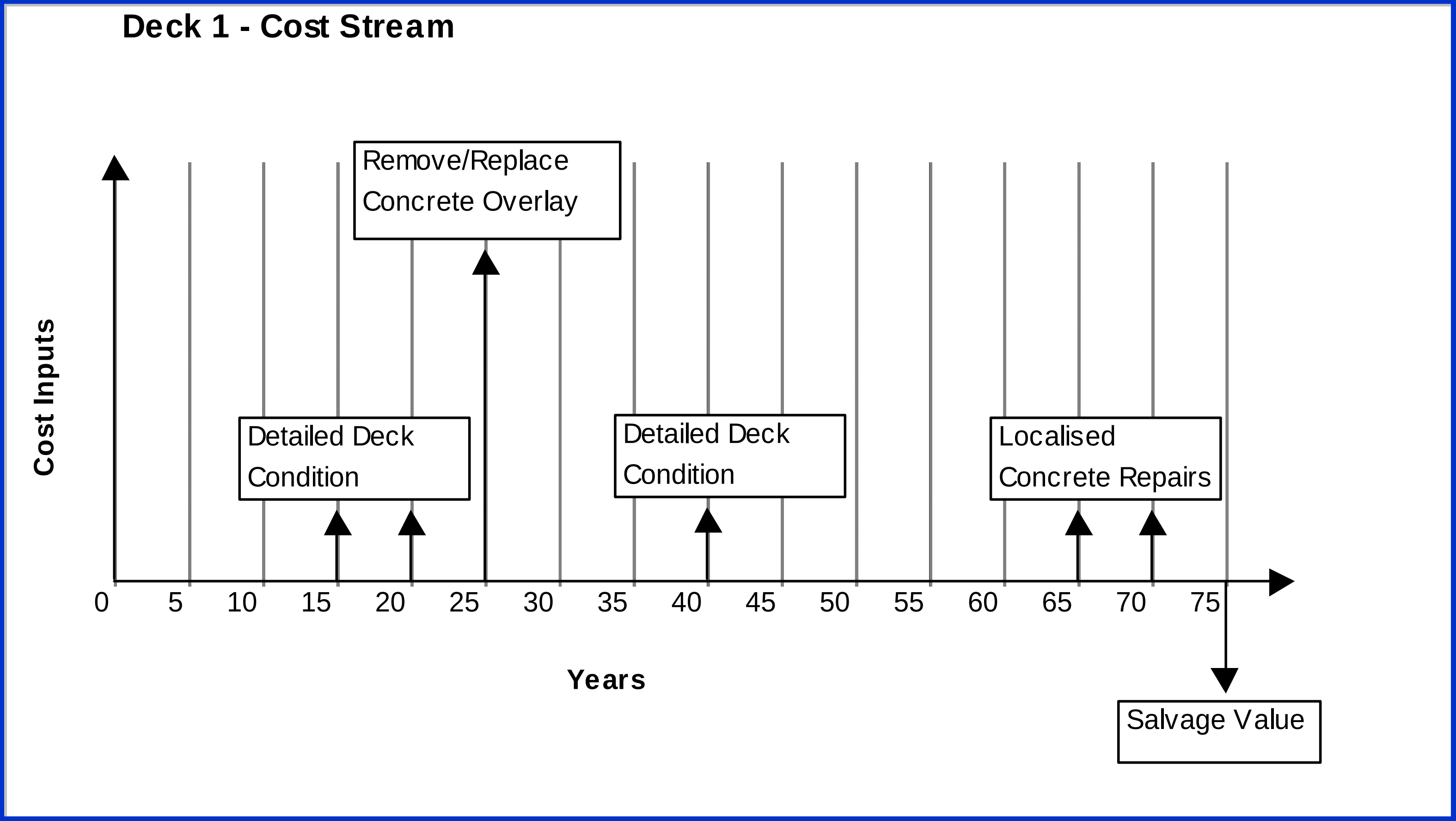
Maintenance Cycles

- Scenario 3 - Deck 1
  - Surface exposed for 35 years
  - Deck life = 40 years therefore 5 years of salvage value



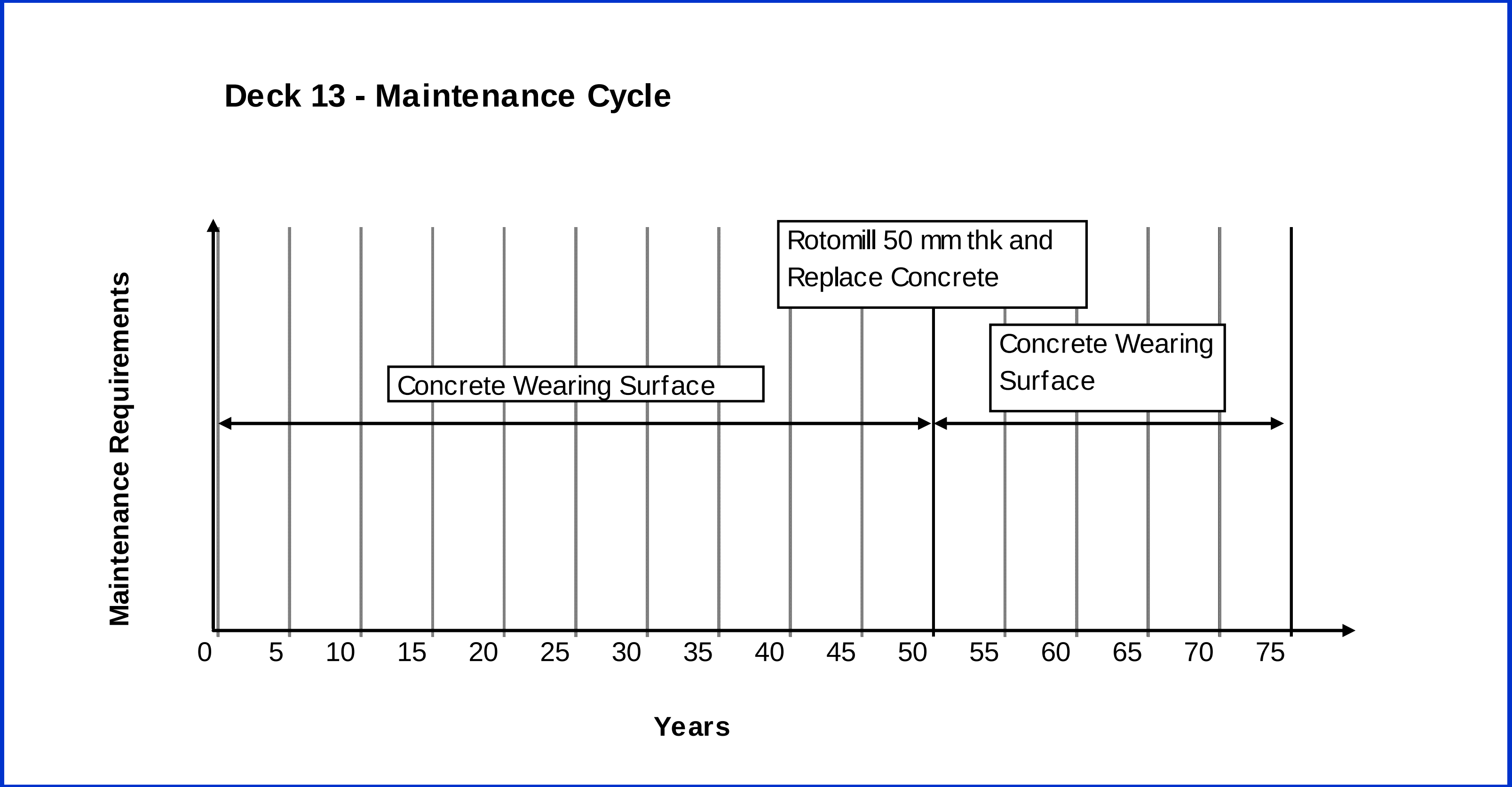
Cost Stream

- Scenario 3 - Deck 1



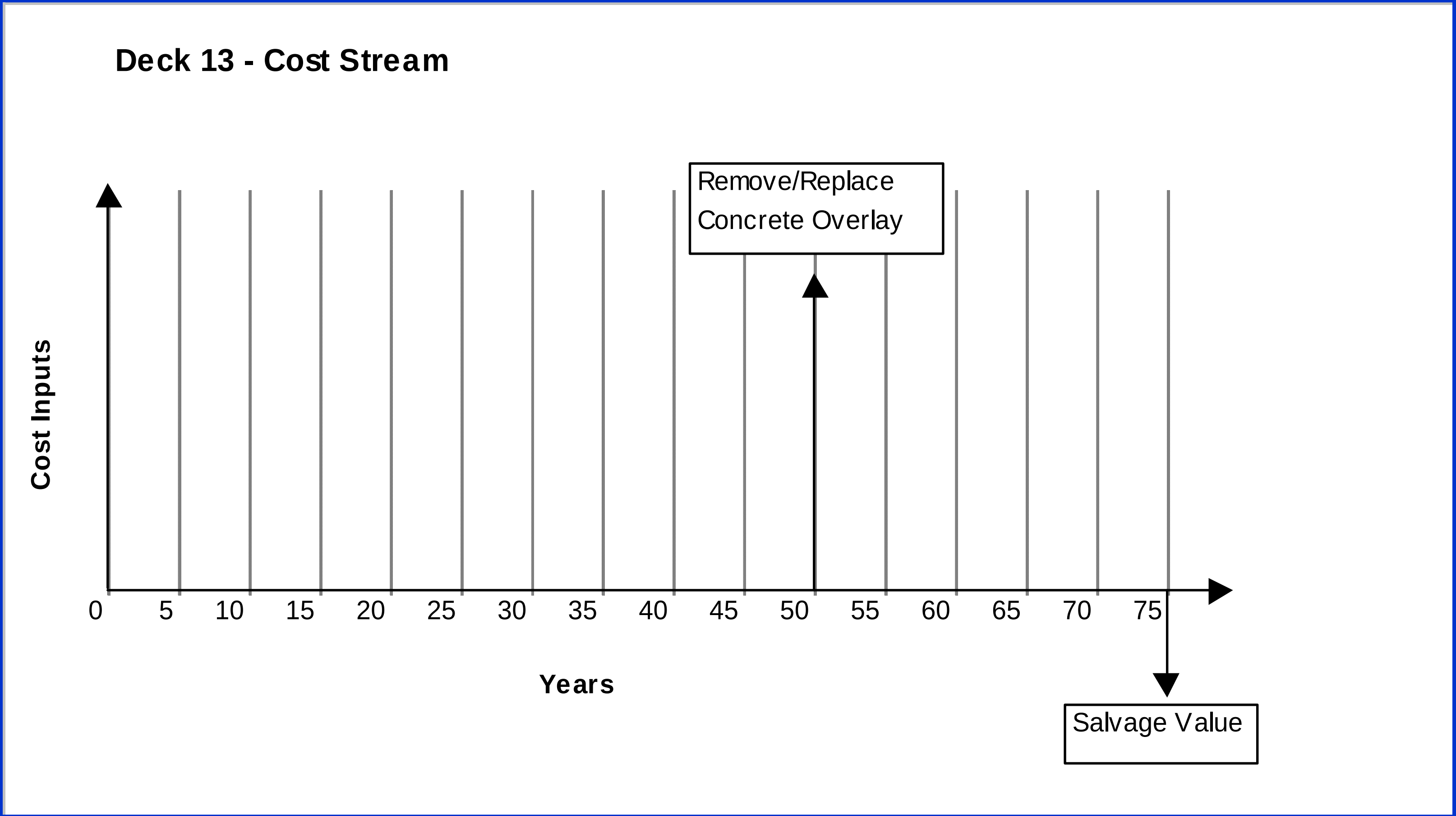
Maintenance Cycles

- Scenario 3 - Deck 13
  - Concrete Surface Replaced at Year 50 based on Concrete Deterioration
  - Deck life = 100 years



Cost Stream

- Scenario 3 - Deck 13



Net Present Value Analysis

- 3 Scenarios
  - Scenario 1 - 90 mm thick asphalt wearing with waterproof membrane assuming a chloride diffusion rate similar to normal performance concrete
  - Scenario 2 - Same as 1 except assumed a chloride diffusion rate based on high performance concrete
  - Scenario 3 - 50 mm thick high density concrete overlay assuming a chloride diffusion rate based on high performance concrete

Sensitivity Analysis

- Cost defined as well defined or variable
  - Well Defined
    - Quantities
    - Initial cost of concrete, reinforcement, overlays
  - Variable
    - Amount and cost of localised deck surface repairs
    - Effective interest rate
    - Service life of deck alternatives
- Variables were compared using a sensitivity analysis

Sensitivity Analysis

- Cost of localised deck surface repairs compared at $\$400/m^2$ and $\$600/m^2$
- Effective interest rates used were 3% and 5%
- Service life of deck systems compared in Scenarios 1 and 2

Results - Scenario 3 Continuous Spans

	Deck Systems					
Deck System (Reinforcement)	Deck 1 (Black)	Deck 13 (CRD GFRP)	Deck 10 (CRD Black)	Deck 3 (Epoxy)	Deck 4 (MMFX2)	Deck 4 (GFRP)
Rank	1	2	3	4	5	9
Initial Deck Construction Cost	$2,184,353	$2,468,074	$2,246,295	$2,368,778	$2,443,149	$3,018,25 9
Difference from Deck 1		$283,721	$61,942	$96,916	$258,795	$833,905
Mean NPV	$2,448,322	$2,482,119	$2,485,358	$2,529,652	$2,567,794	$3,019,04 0
Ratio Compared to Deck 1		1.01	1.02	1.03	1.05	1.23
Max/Min Difference from Mean NPV	+/-$63,055	+/-$30,628	+/-$58,057	+/-$47,469	+/-$30,277	+/- $11,222

Results - Scenario 3 Simple Spans

	Deck Systems					
Deck System (Reinforcement)	Deck 13 (CRD GFRP)	Deck 14 (CRD w. GFRP /Black)	Deck 4 (GFRP /Black)	Deck 10 (CRD Black)	Deck 1 (Black)	Deck 2 (Epoxy)
Rank	1	2	3	4	5	6
Initial Deck Construction Cost	$1,786,735	$2,103,119	$2,188,938	$2,045,200	$2,076,247	$2,216,84 5
Difference from Deck 1	-$289,812	$26,872	$112,692	-$31,046		$140,598
Mean NPV	$1,815,782	$2,201,026	$2,284,919	$2,284,263	$2,340,215	$2,379,08 3
Ratio Compared to Deck 1	0.78	0.94	0.98	0.98		1.02
Max/Min Difference from Mean NPV	+/-$6,422	$18,978	+/-$17,788	+/-$58,057	+/-$63,055	+/-48,312

Conclusions

- Reasonable to assume a service life of 100 years for GFRP reinforcement embedded in concrete
- For simple span bridges, steel-free deck slab reinforced with GFRP is the most cost-effective both from an initial cost perspective and life cycle cost perspective
- Steel-free deck slab with GFRP reinforcement is more cost-effective for simple span bridges than continuous span bridges

Recommendations for GFRP

- Further field investigations in areas of higher stress levels
- Research into concrete mixes with lower pH levels initially
- Standardized test procedures for accelerated testing that replicates embedment in concrete
- Further research into the required properties for the protective coatings (i.e. thickness, application)

Final Thought

What is the long-term failure mode of SFD with GFRP reinforcement?

- Is it the GFRP?
- Or is it the concrete?

Thank You!

Questions?

Chloride Diffusion Rates

Depth of Bar (mm)	Time to Reach Chloride Threshold (Years)					
	Life-365				Fick's Second Law	
	Concrete Type		3x's Chloride Threshold			
	Normal Concrete w/c = 0.38	HPC 15% Fly Ash + 8% Silica Fume	Normal Concrete w/c = 0.38	HPC 15% Fly Ash + 8% Silica Fume	Chloride Threshold	3x's Chloride Threshold
25	7.6	21.6	15.2	*(40.6)	2.9	17.3
50	15.4	*(57.1)	26.7	*(119.8)	11.7	69.2
75	24.5	*(114.4)	*(44.5)	*(256.1)	26.3	155.7
100	*(35.6)	*(195.2)	*(69.5)	*(444.9)	46.8	276.8
125	*(49.6)	*(298.9)	*(102.2)	*(499.7)	73.1	432.5
150	*(66.7)	*(425.9)	*(143.7)	*(499.7)	105.3	622.8