Life Cycle Cost Analysis Based on Service Life Modeling for NX Infrastructure

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Corrosion Mitigation

- Consequences of corrosion can not be ignored

- Available Strategies
  - Corrosion Resistant Reinforcing Steels
  - High Performance Concrete

Wiss, Janney, Elstner Assoc. (WJE)

- Troubleshoot existing structures
  - Have perspective on what causes failures and how to prevent them

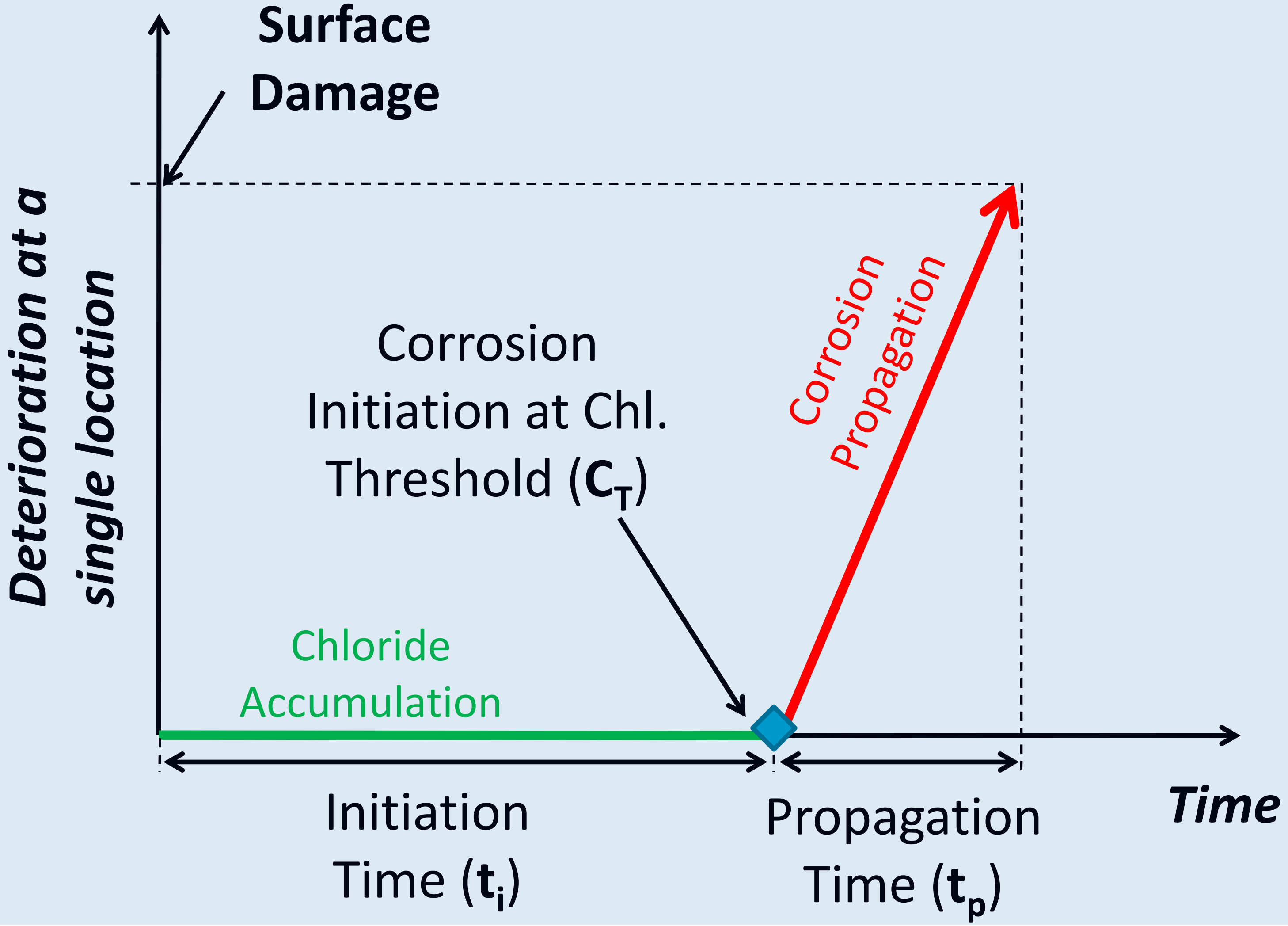
- Research history of alternatives to black bar
  - 1998 FHWA-RD-98-153: “new breed” bar studies
  - Field performance investigations with various DOTs and CRSI – service life models

Life Cycle Cost Analysis

- Recommended by FHWA as method for choosing between alternatives

- This study compares **Annualized Costs**
  1. Performance in typical bridge deck modeled based on bar properties
  2. Total direct costs calculated over life of bridge
     - Includes construction, maintenance, but no User costs
  3. Convert to equivalent annual cost

Model for Damage

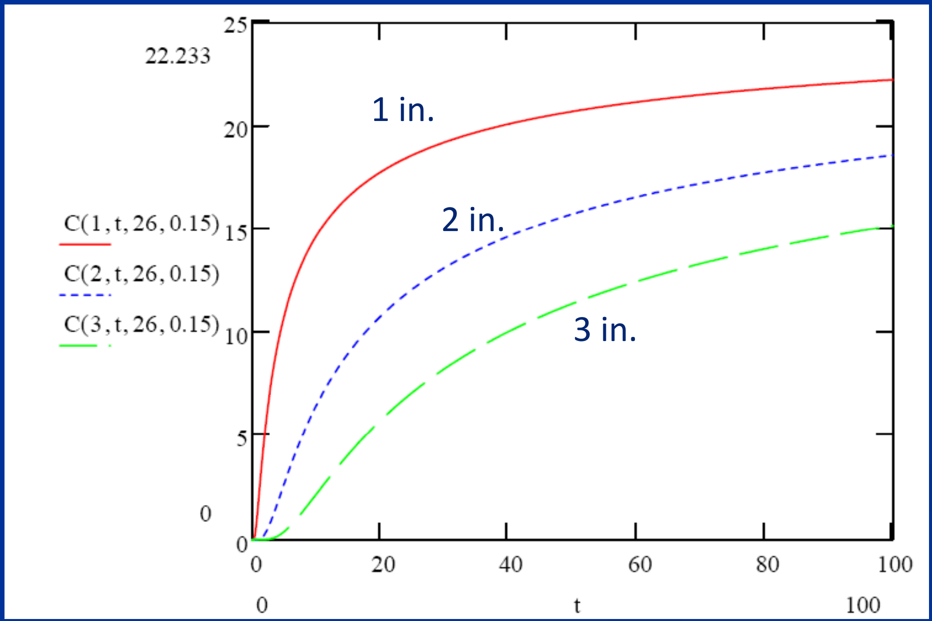


Chloride Penetration

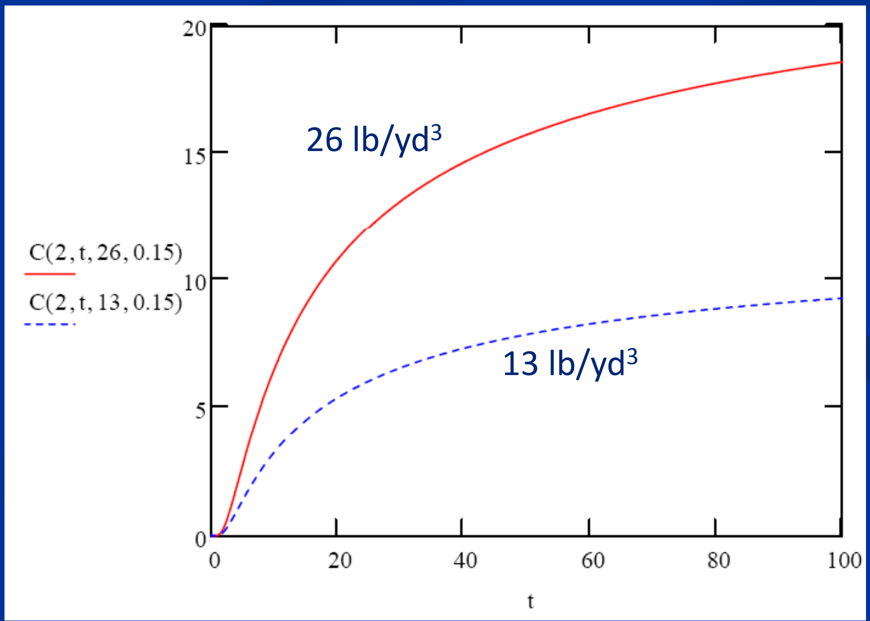
- Ingress of chloride governed by Fick's Law Sol'n:

$$C(x, t, C_s, D) := (C_s - C_0)\cdot\left(1 - \operatorname{erf}\left(\frac{x}{2\cdot\sqrt{D\cdot t}}\right)\right) + C_0$$

Effect of Depth



Effect of C_S



Corrosion Initiation Model

- Initiation time (t_i) modeled based on Chloride threshold (C_T) and cumulative distribution functions based on field data for:
  - Surface concentration (C_s)
  - Diffusion coefficient (D_0)
  - Cover depth
- Considered cracks over 5% of area as 5x Diffusion coefficient elsewhere

Modeling challenges

- Determination of Inputs (C_T, t_p)
  - Corrosion resistant bars require **long** or **accelerated** tests; most do **not** assess **t_p**
  - Wide variety of opinions in industry

- Stainless clad bar
  - Effect of bar ends, breaks in cladding
    - Clad bar treated as 316 stainless with bar ends performing as black bar in 1.4% of deck area

Model inputs

- Cover a range of expected performance (pessimistic to optimistic)

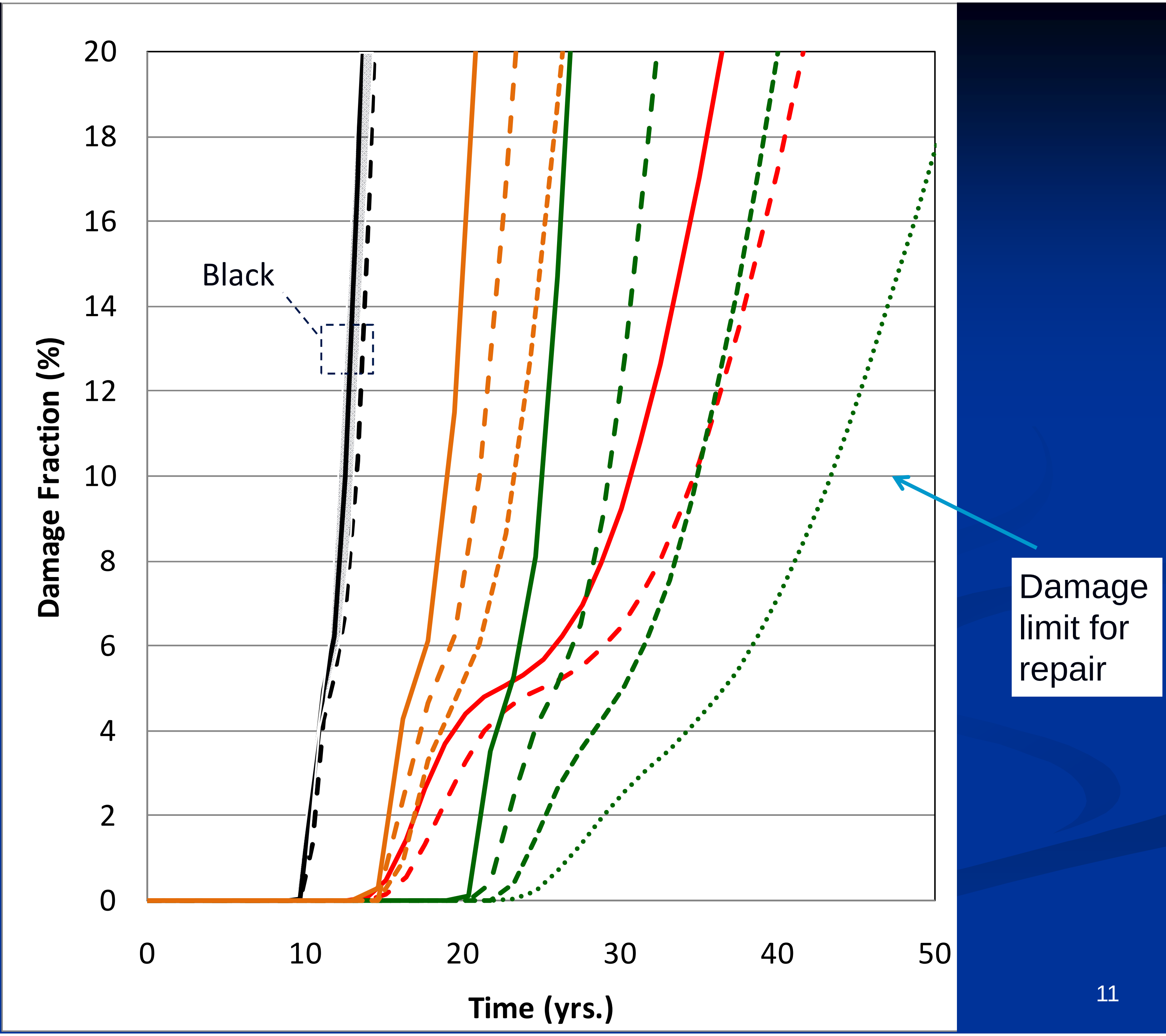
Case	Corrosion Threshold, CT (lbs/yd^3)	Propagation time, tp (yrs)
Black	1, 1.5	5
ECR	3, 6, 9, 12	15
MMFX-II	3, 4.5, 6	9
Stainless Clad (SCR)	10, 15, 25	25
304 SS	7.5, 15	20
316 SS	10, 15, 25	25

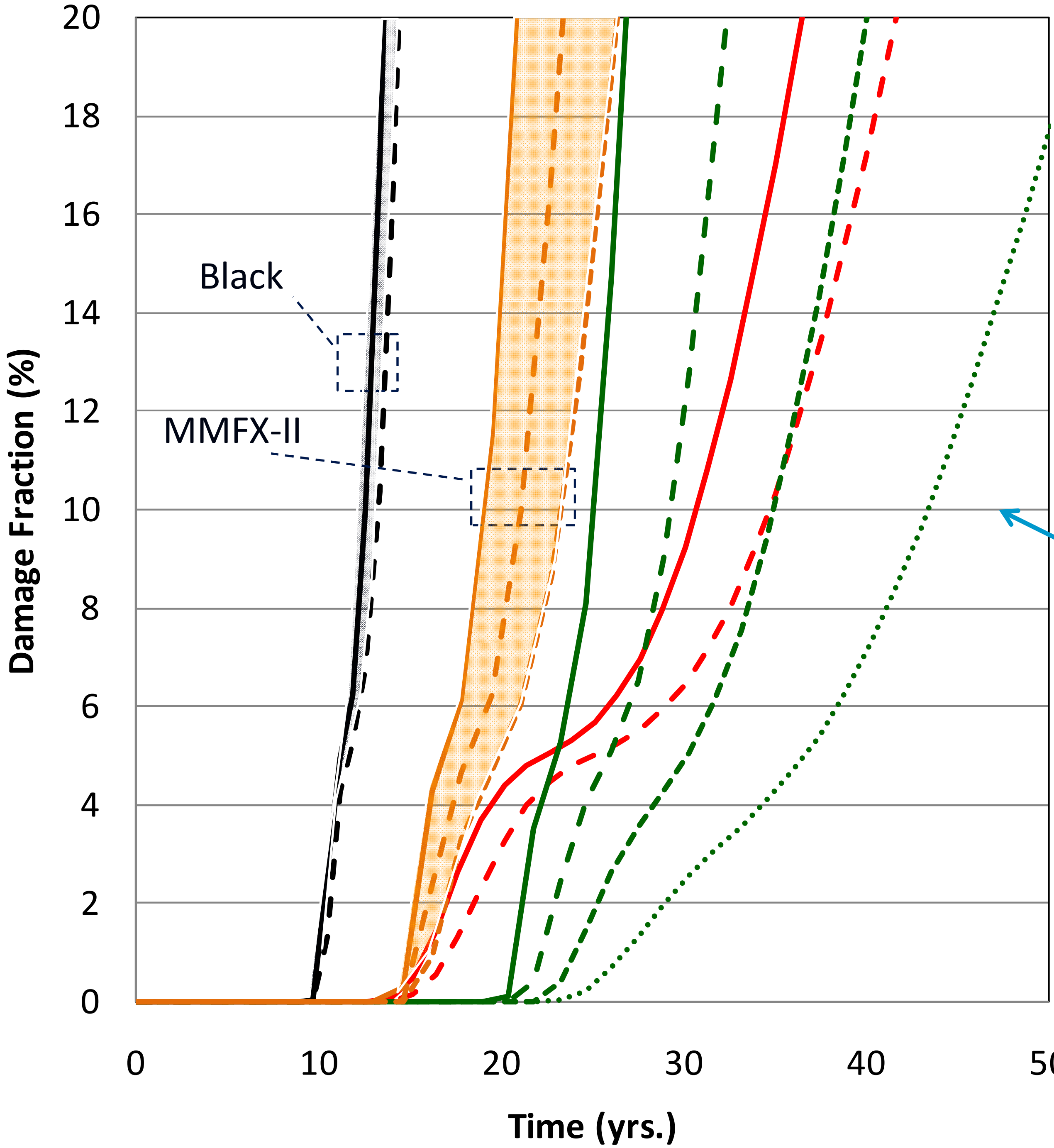
Model Inputs

Concrete and Exposure Distributions:

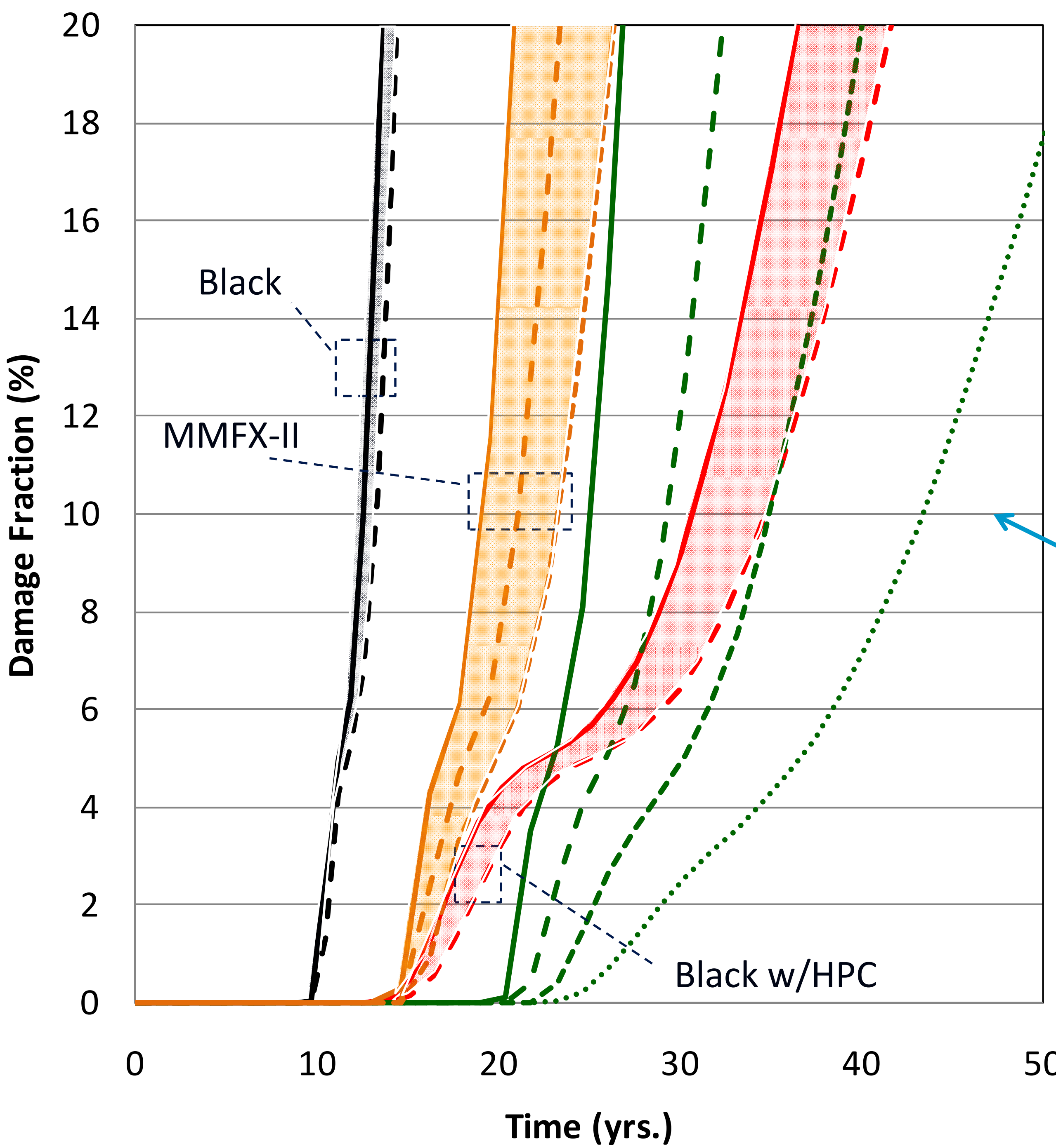
Bridge Property	Average (Coef. of Var.)
Concrete Cover (Bridge Construction)	3 in. (10%)
Diffusion Coefficient (Concrete Quality)	0.15 in^2/yr, 0.025 in^2/yr for HPC (45%)
Surface Chloride Concentration (Exposure Conditions)	26 lbs/yd^3 (22%)

Values based on WJE field studies in Iowa and Virginia of 9 decks, but severe exposure

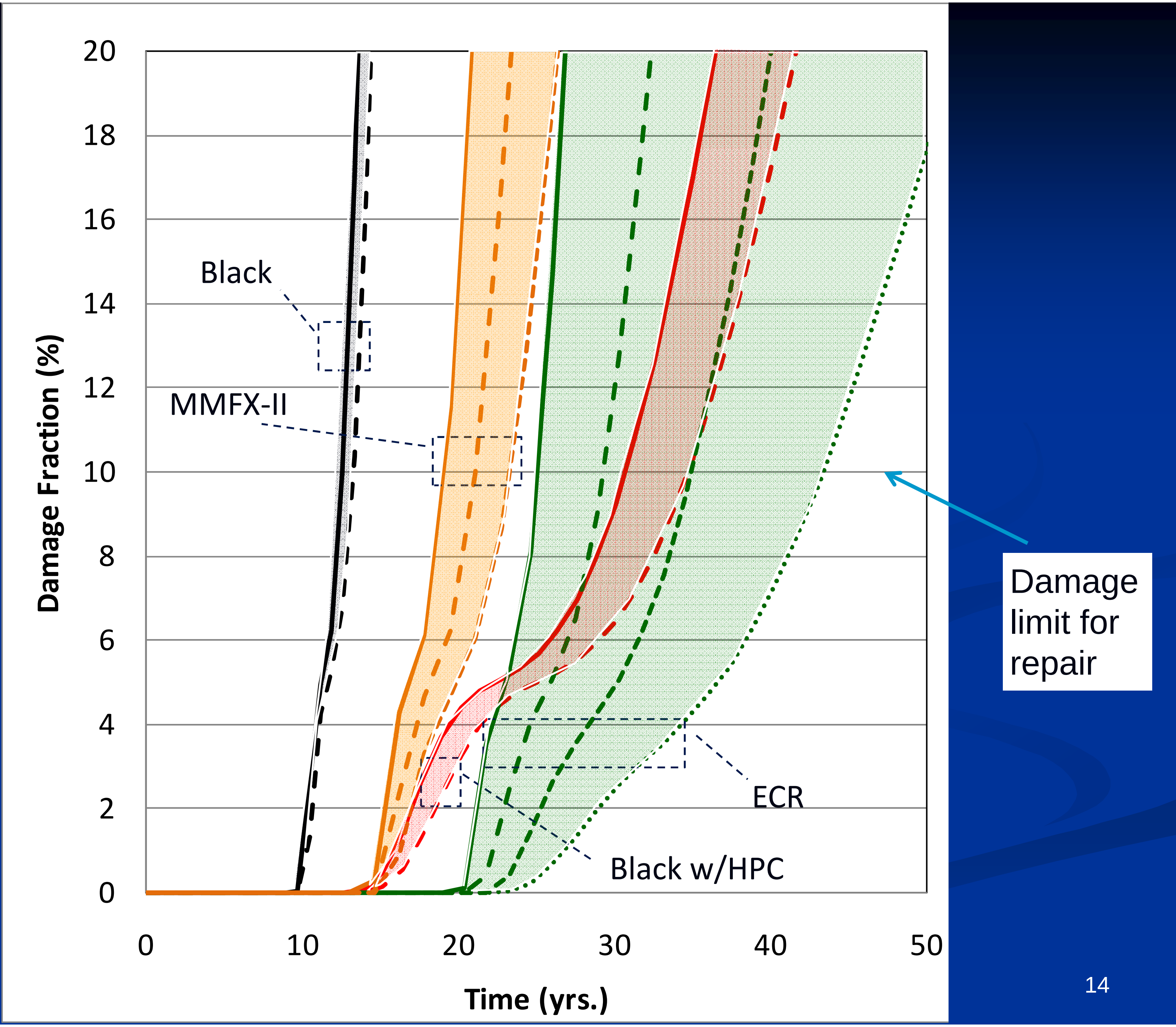

20
18
16
14
12
10
8
6
4
2
0
Damage Fraction (%)
Black
0
10
20
30
40
50
Time (yrs.)
Damage limit for repair



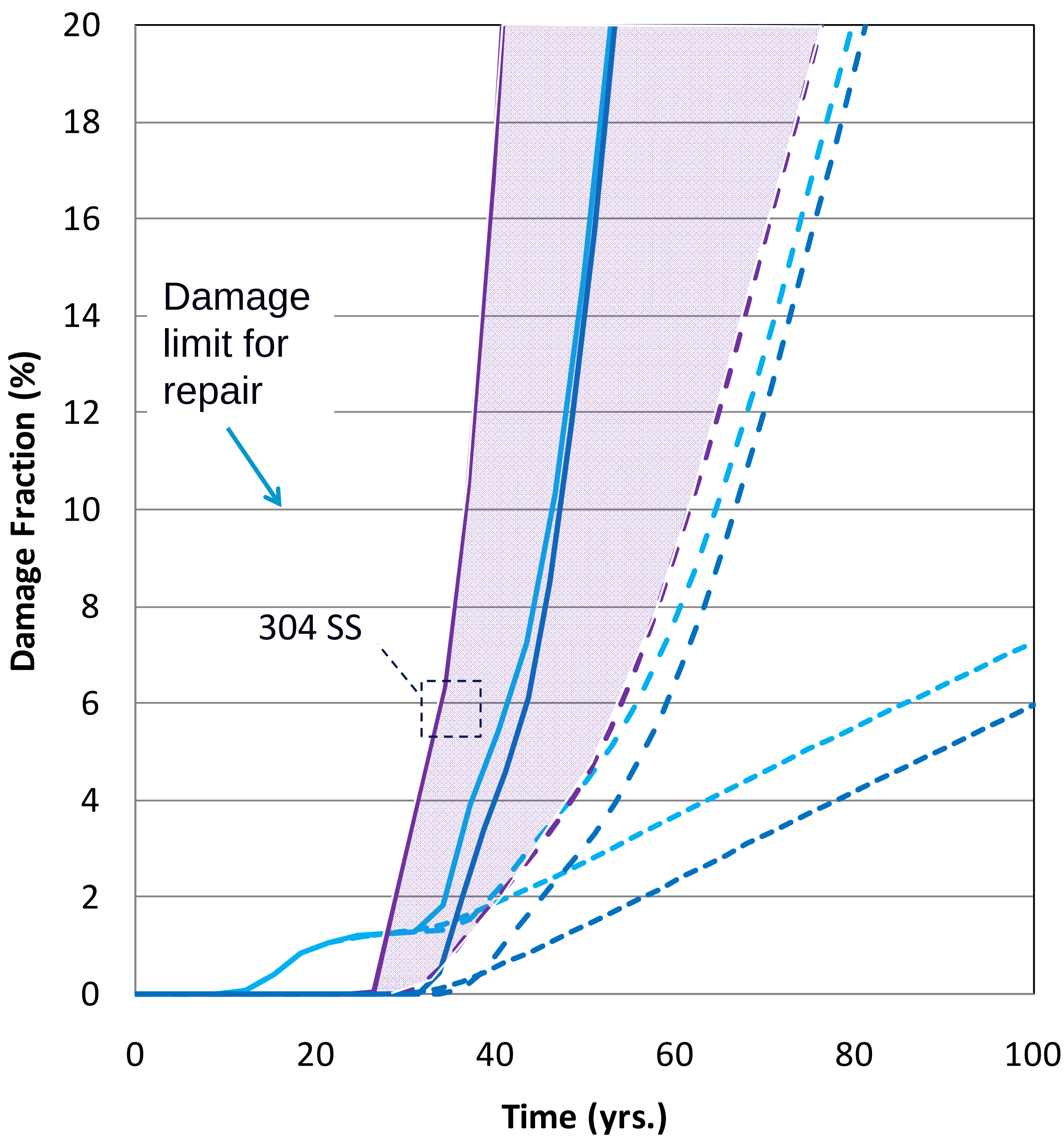
Damage limit for repair



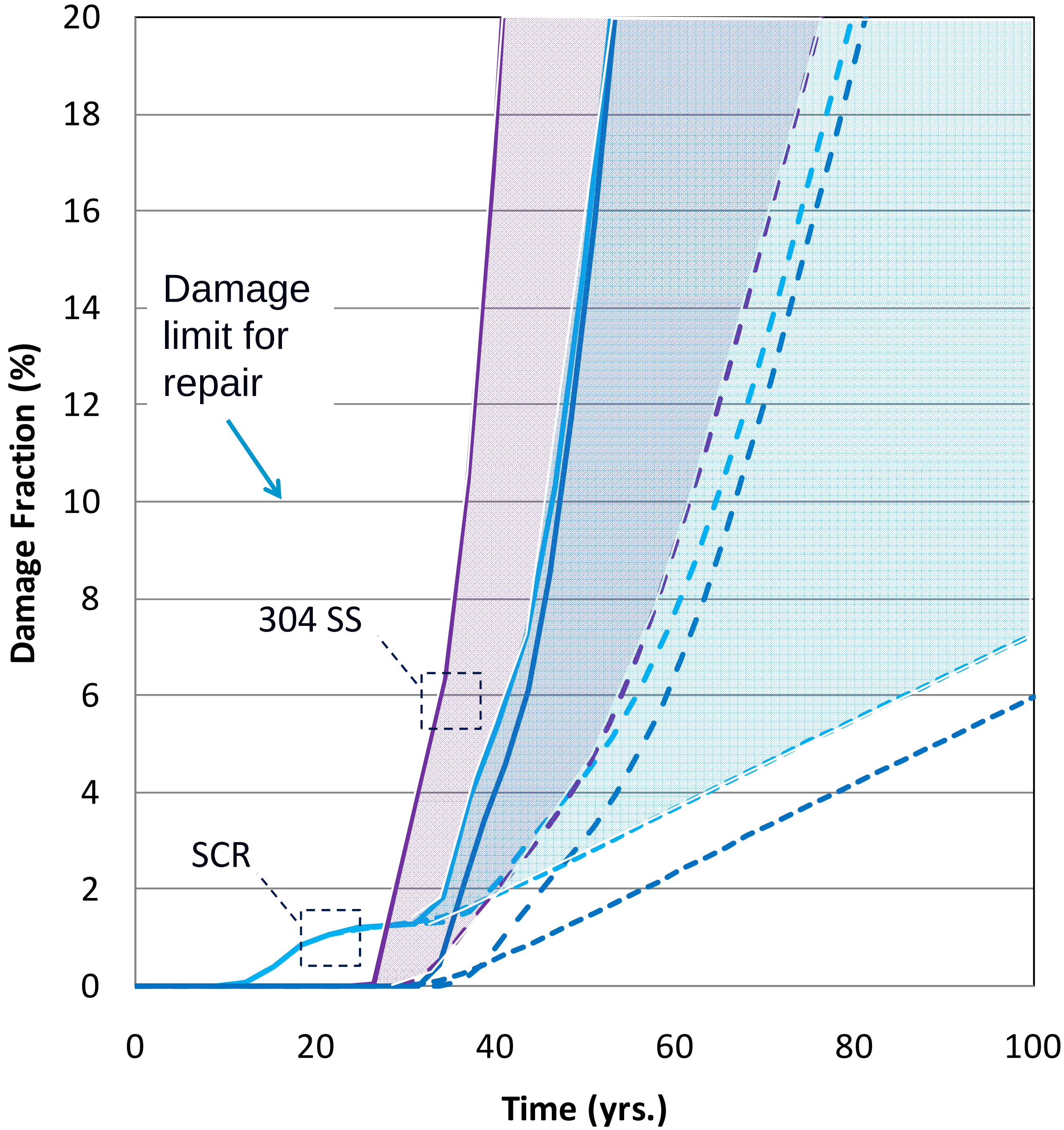
Damage limit for repair



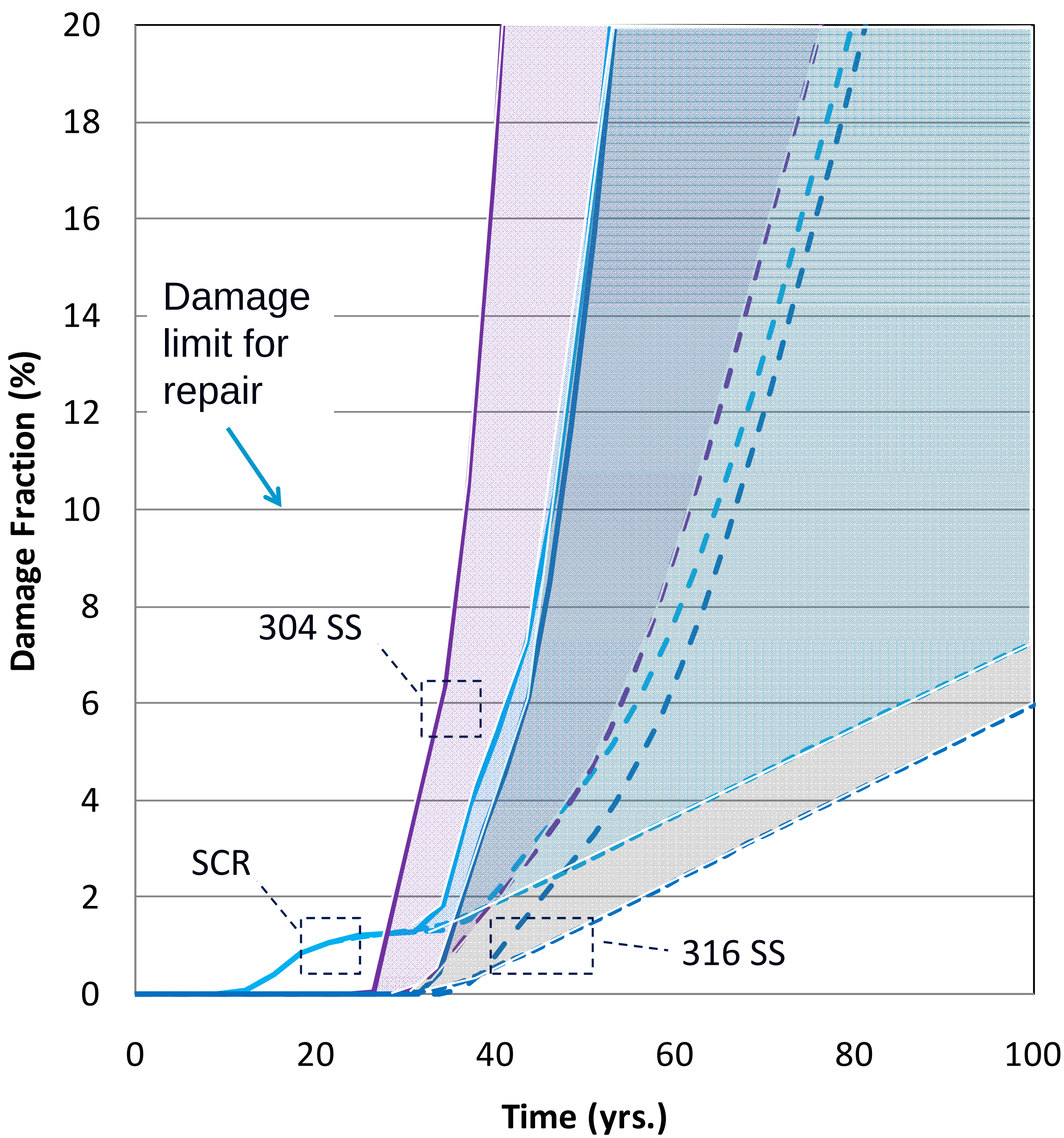
Damage Fraction (%)
20
18
16
14
12
10
8
6
4
2
0
0
10
20
30
40
50
Time (yrs.)
Black
MMFX-II
ECR
Black w/HPC
Damage limit for repair



Damage Fraction (%)
20
18
16
14
12
10
8
6
4
2
0
Damage limit for repair
304 SS
0
20
40
60
80
100
Time (yrs.)



Damage Fraction (%)
20
18
16
14
12
10
8
6
4
2
0
Damage limit for repair
304 SS
SCR
0
20
40
60
80
100
Time (yrs.)



Damage Fraction (%)
20
18
16
14
12
10
8
6
4
2
0
Damage limit for repair
304 SS
SCR
316 SS
0
20
40
60
80
100
Time (yrs.)

Economic Analysis Inputs

- Maintenance Program
  - Patching starts at 1% damage and deck is patched up to 10% of the area before an overlay is placed.
  - Deck is overlaid when damage level reaches 10%.
  - After two overlays, the deck service life is complete.
  - Total life span of all decks is terminated at 100 years.

Economic Analysis Inputs

- Real discount rate (corrected for inflation):
  - 2.8% - 2008 US OMB Circular A-94
  - 4%

- Overlay (finite life span):
  - 7 yrs.
  - 15 yrs. – Average based on WJE survey
  - 25 yrs.

Economic Analysis Inputs

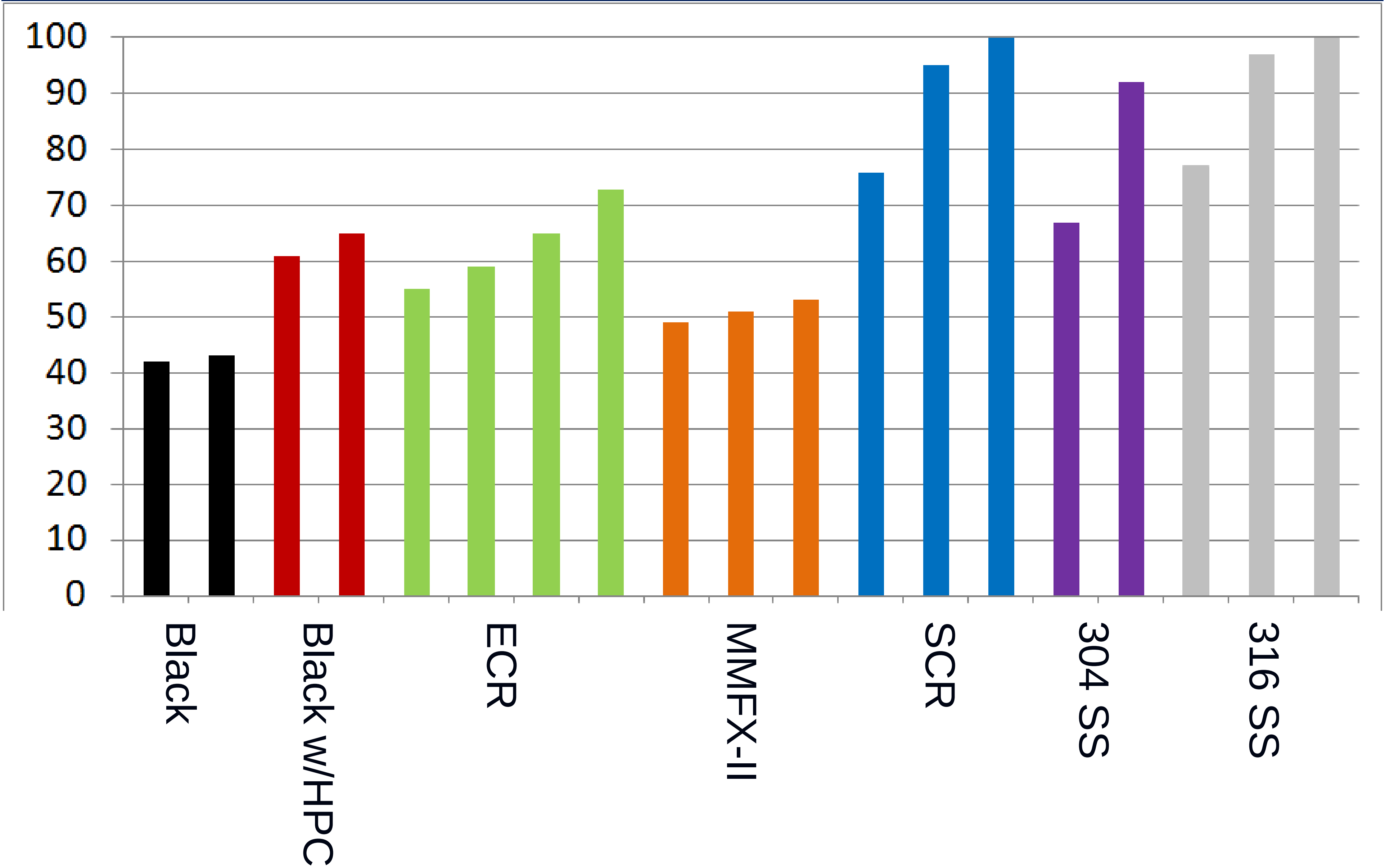
- **Bridge costs** determined based on "average"-sized bridge (FHWA report)

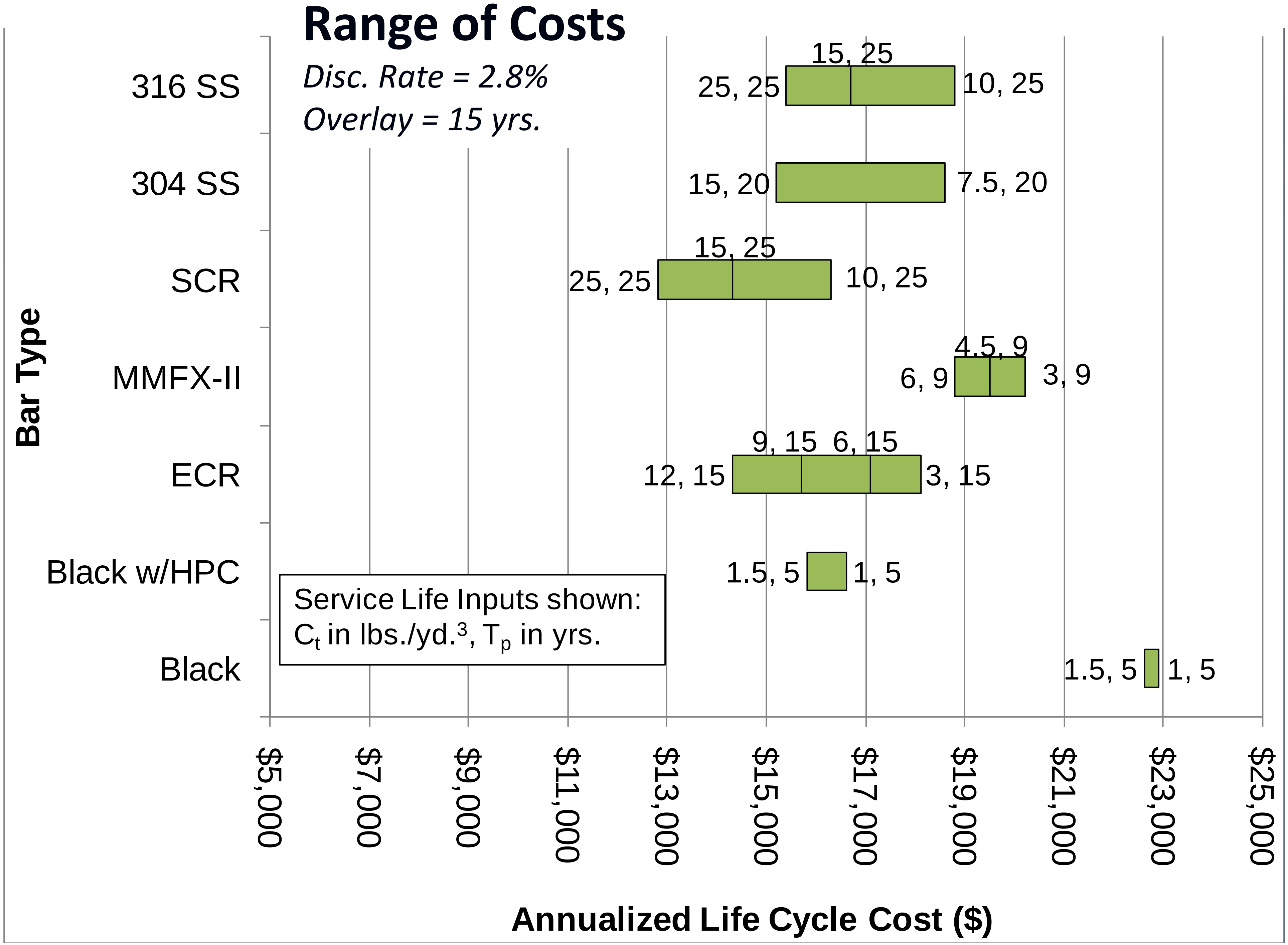
- **Bar costs** used for initial bridge deck costs based on April 08 pricing provided by NX Infrastructure

Bar Type	Black	ECR	MMFX-II	Clad	304 SS	316 SS
Cost ($/lb) – Fab'd and Delivered	0.94	1.15	1.13	2.90	3.46	4.95

- **HPC cost** - Material 150% of that for conventional conc.

Deck Life Spans (Overlay Life=15 yrs)




Range of Costs
Disc. Rate = 2.8%
Overlay = 15 yrs.
Bar Type
316 SS
304 SS
SCR
MMFX-II
ECR
Black w/HPC
Black
15, 25
25, 25
10, 25
15, 20
7.5, 20
15, 25
25, 25
10, 25
4.5, 9
6, 9
3, 9
9, 15
6, 15
12, 15
3, 15
1.5, 5
1, 5
1.5, 5
1, 5
Service Life Inputs shown:
C_t in lbs./yd.^{3}, T_p in yrs.
$5,000
$7,000
$9,000
$11,000
$13,000
$15,000
$17,000
$19,000
$21,000
$23,000
$25,000
Annualized Life Cycle Cost ($)

Effect of Overlay Life

- Longer Overlay Life = Decreased Annualized Cost

- Most corrosion resistant alternatives appear better if overlay life is short

- Regardless of overlay life, SCR (25 lbs/yd^3) has lowest Annualized Cost

Effect of Discount Rate

- Higher discount rate = Increased Annualized Cost
  - Future costs weighted less heavily versus initial costs

- For 2.8% discount rate, SCR (25 lbs/yd^3) has lowest Annualized Cost

- For ≥4% discount rate, ECR (12 lbs/yd^3) has lowest Annualized Cost

Best Estimate for SCR

- Overlay = 15 yrs., Rate = 2.8%
- Consider Annualized Cost for Optimistic corrosion resistance:
  - SCR is 43% less than Black Bar
  - SCR is 10% less than ECR
  - SCR is 17% less than Solid 316 SS

Conclusions

- Modeled Range of Inputs Due to Uncertainties: Corrosion resistance, Material Costs, Discount Rate, Overlay life, **User Cost**
- SCR showed lowest Annualized Cost (2.8%, 15 yrs.) even with bar ends treated as black
- Model is available for specific projects

Questions?

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Effect of User Costs

- User Costs - $ value assigned to public
- Simple Example
  - Traffic congestion on average bridge due to:
    - 150-day construction
    - 45-day rehabilitation
  - Assumed delay time, $/hr

Effect of User Costs

- Results of User Cost analysis
  - Produces 4-6x increase in Annualized costs
  - Benefits of more corrosion resistant alternatives greater
  - SCR (25 lb/yr) still least expensive choice
  - 316 SS replaces ECR as 2^{nd} best alternative