April 5, 2022
ICRI 2022 Spring Convention

Service Life Evaluation of Concrete Structures

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Thornton Tomasetti

ICRI CONCRETE REPAIR
Restore | Repurpose | Renew

Agenda

Part I: Introduction
- Durability
- Code-based vs performance-based design

Part II: Chloride-induced corrosion
- Review of corrosion mechanism
- Introduction of service life modeling

Part III: Service life evaluation
- Diagnostic phase
- Prognostic phase

Part IV: What's next?
- Artificial intelligence and digital twins

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Part I

Durability

Durabilĭtas = Ability to last for a long time

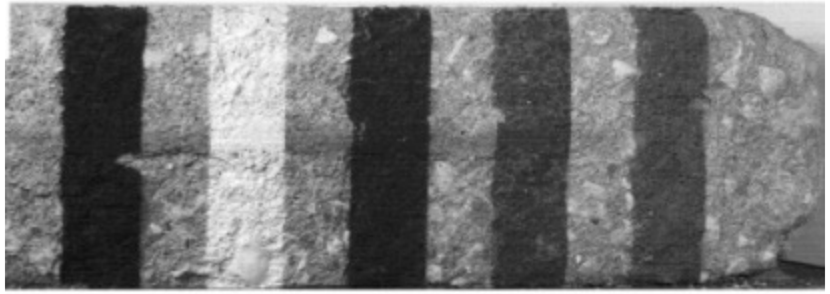
ACI definition:

durability —	the ability of a material to resist weathering action, chemical attack, abrasion, and other conditions of service.

Concrete durability

Various mechanisms of deterioration

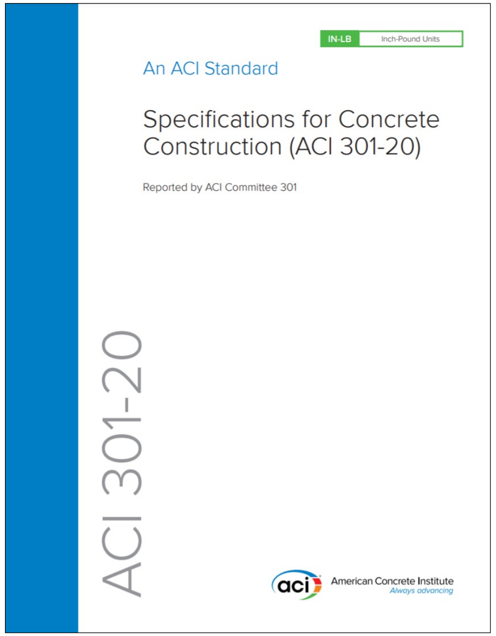
- Freeze and thaw
- Abrasion
- Carbonation
- Chlorides
- Sulfates
- Alkali-silicates
- Etc.



(Millman and Giancaspro, 2015)

Concrete durability

Code-based, prescriptive design



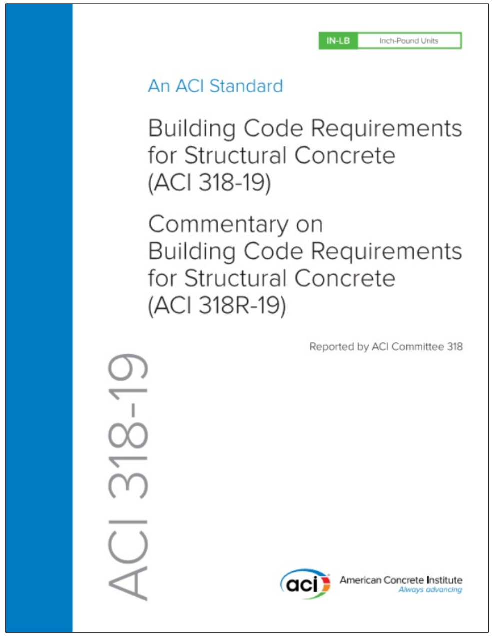
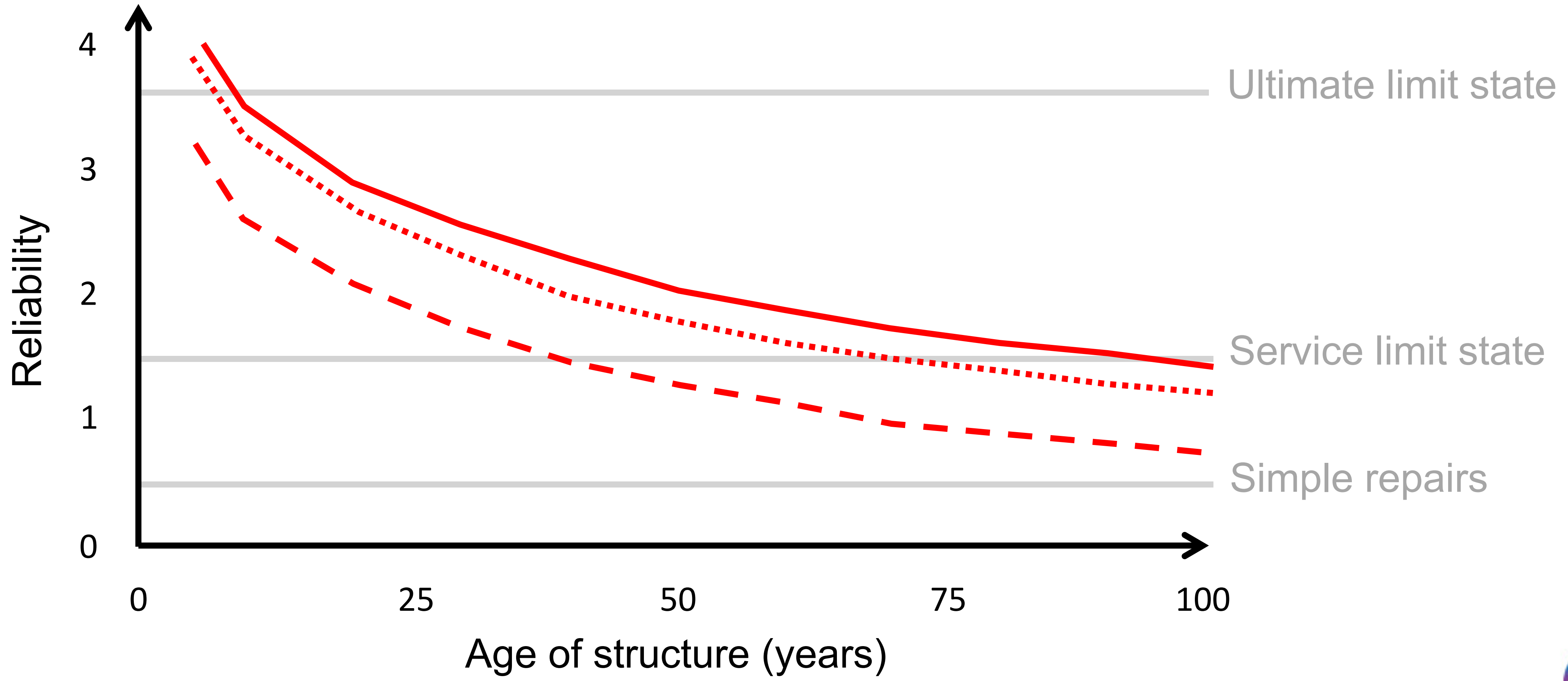


Table 19.3.2.1—Requirements for concrete by exposure class

Exposure class	Maximum w/cm[1,2]	Minimum f_c', psi	Additional requirements: Air content			Limits on cementitious materials
F0	N/A	2500	N/A			N/A
F1	0.55	3500	Table 19.3.3.1 for concrete or Table 19.3.3.3 for shotcrete			N/A
F2	0.45	4500	Table 19.3.3.1 for concrete or Table 19.3.3.3 for shotcrete			N/A
F3	0.40[3]	5000[3]	Table 19.3.3.1 for concrete or Table 19.3.3.3 for shotcrete			26.4.2.2(b)
			Cementitious materials[4] — Types			Calcium chloride admixture
			ASTM C150	ASTM C595	ASTM C1157	
S0	N/A	2500	No type restriction	No type restriction	No type restriction	No restriction
S1	0.50	4000	II[5][6]	Types with (MS) designation	MS	No restriction
S2	0.45	4500	V[6]	Types with (HS) designation	HS	Not permitted
S3 Option 1	0.45	4500	V plus pozzolan or slag cement[7]	Types with (HS) designation plus pozzolan or slag cement[7]	HS plus pozzolan or slag cement[7]	Not permitted
S3 Option 2	0.40	5000	V[8]	Types with (HS) designation	HS	Not permitted
W0	N/A	2500	None			
W1	N/A	2500	26.4.2.2(d)			
W2	0.50	4000	26.4.2.2(d)			
			Maximum water-soluble chloride ion (Cl^-) content in concrete, percent by mass of cementitious materials[9,10]		Additional provisions	
			Nonprestressed concrete	Prestressed concrete		
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	Concrete cover[11]	

Concrete durability

Performance-based design



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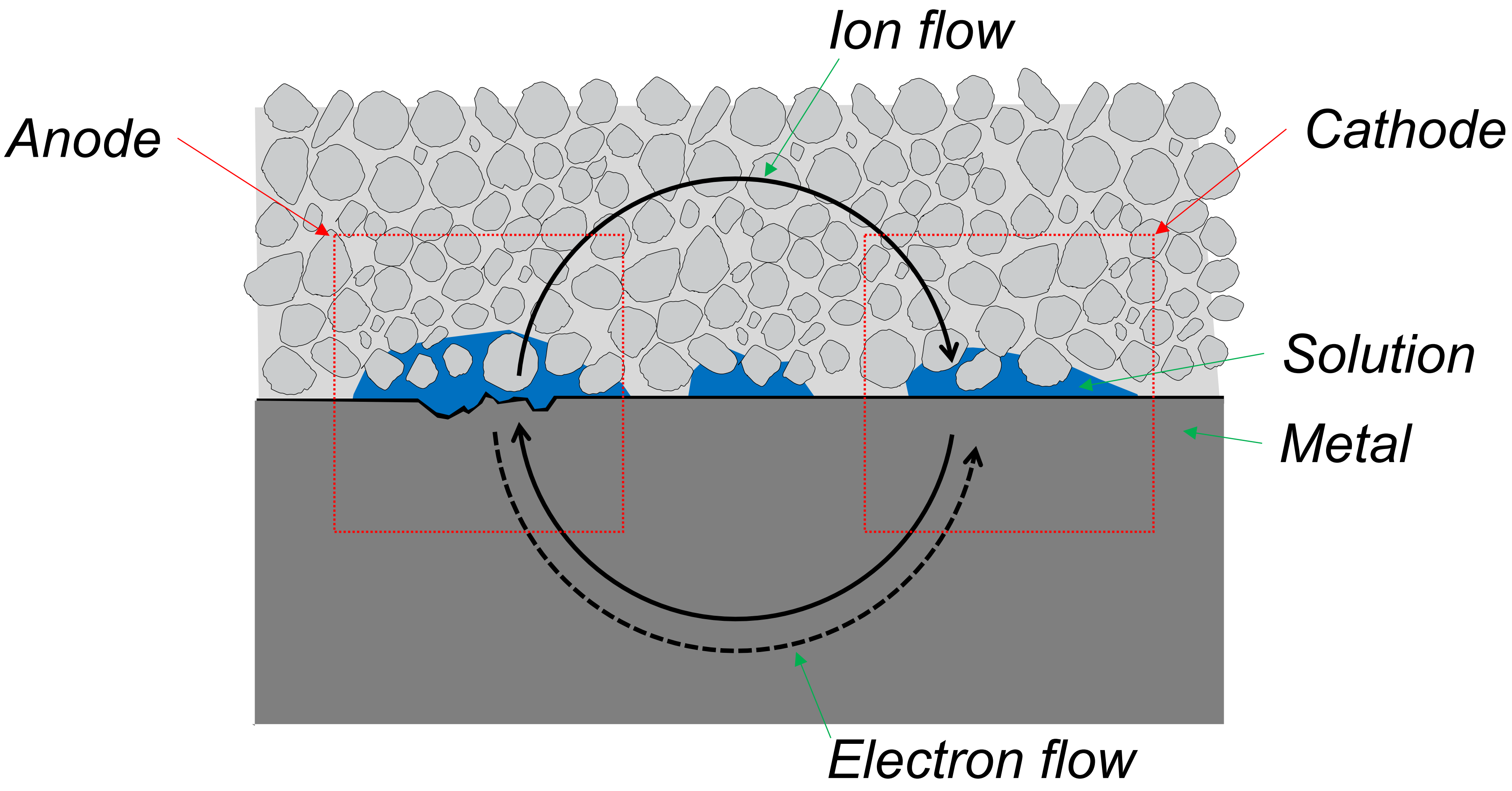
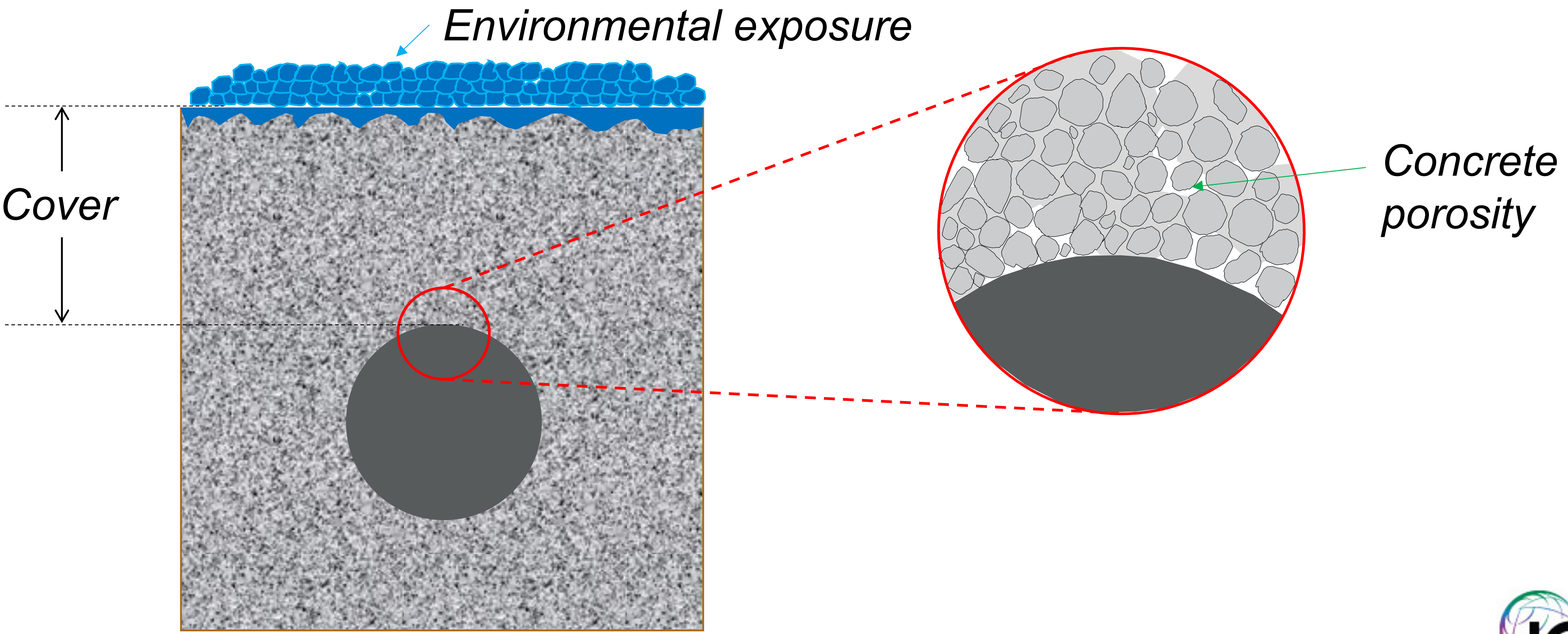
Part II

Chloride-induced corrosion



Service life model

Corrosion initiation (or depassivation of the steel reinforcement)



Service life model

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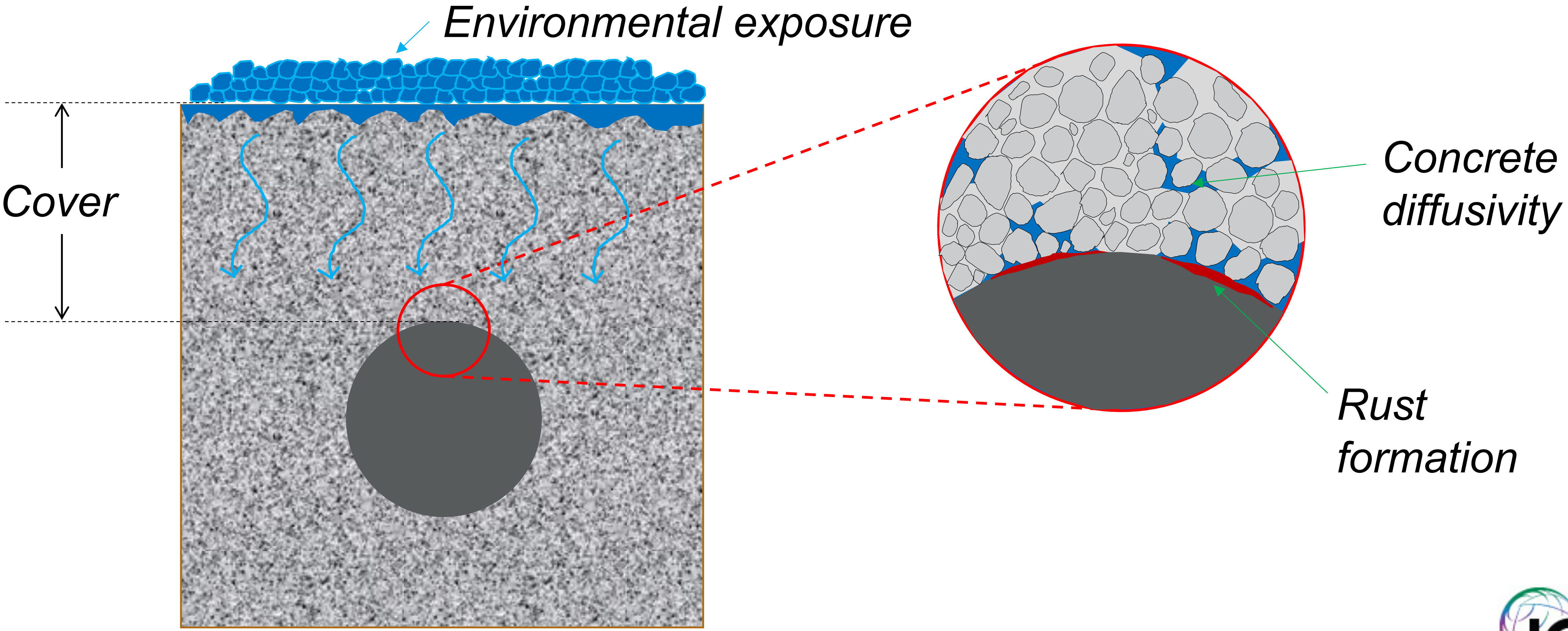
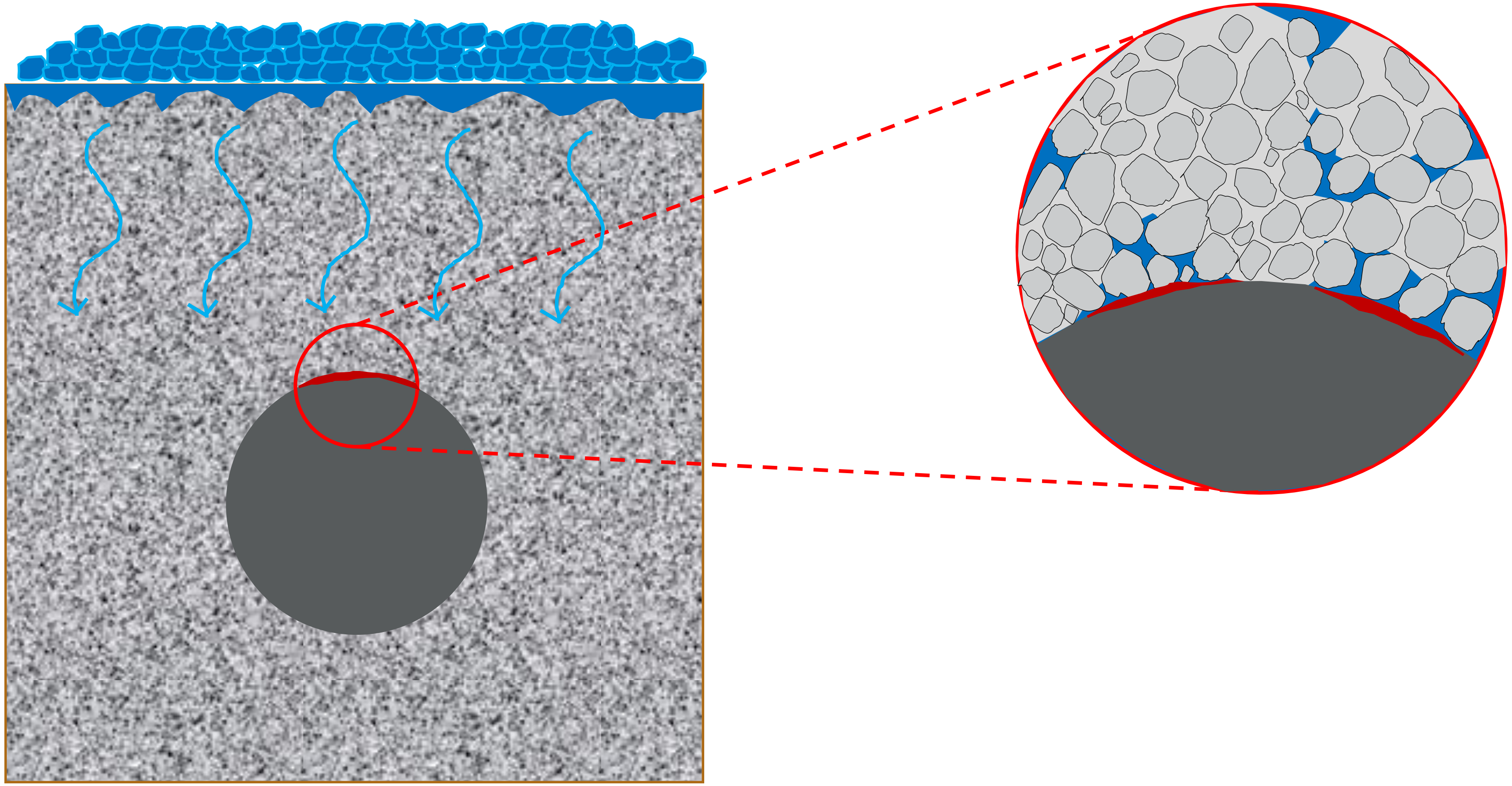


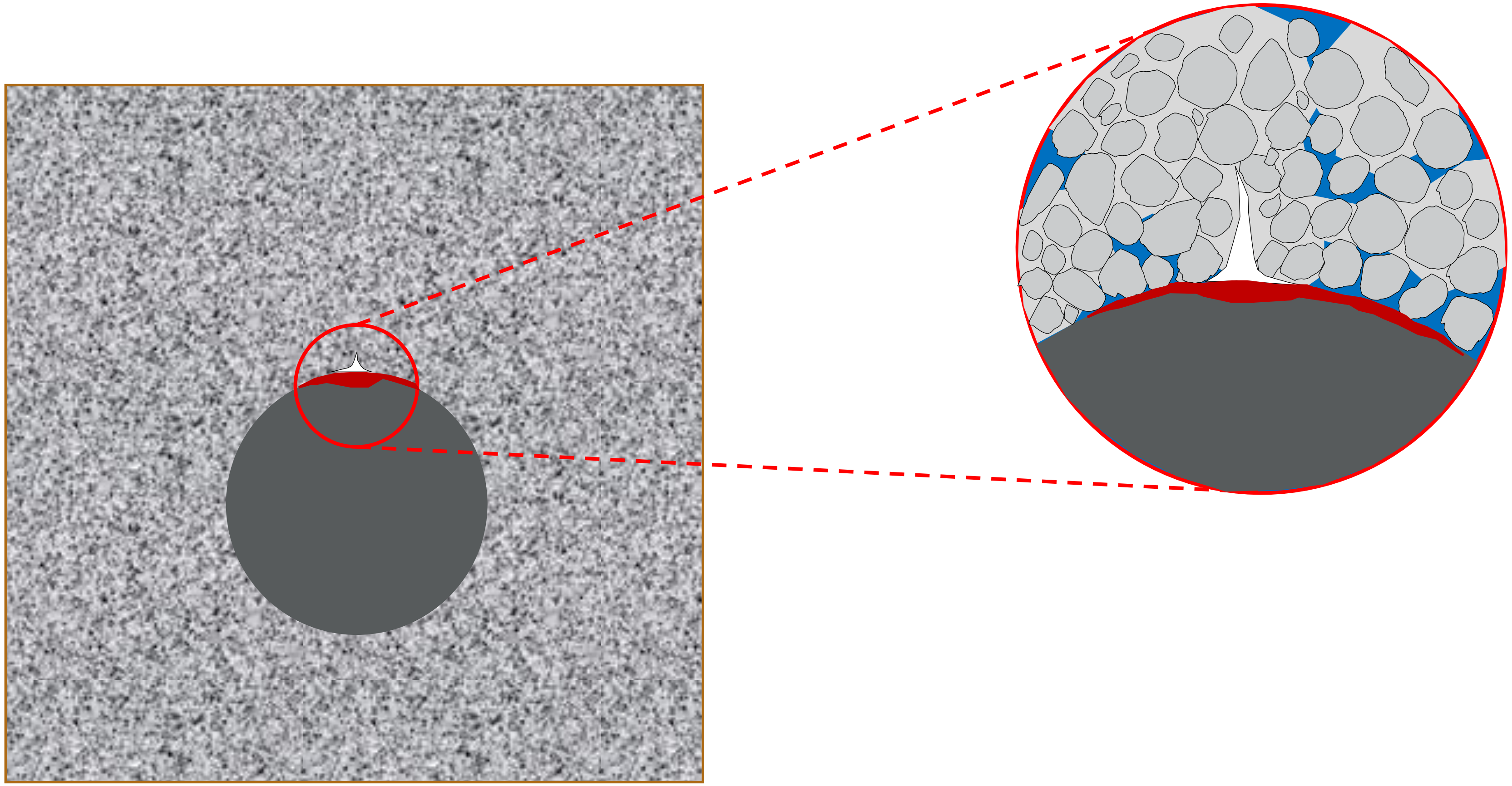
Service life model

Corrosion propagation



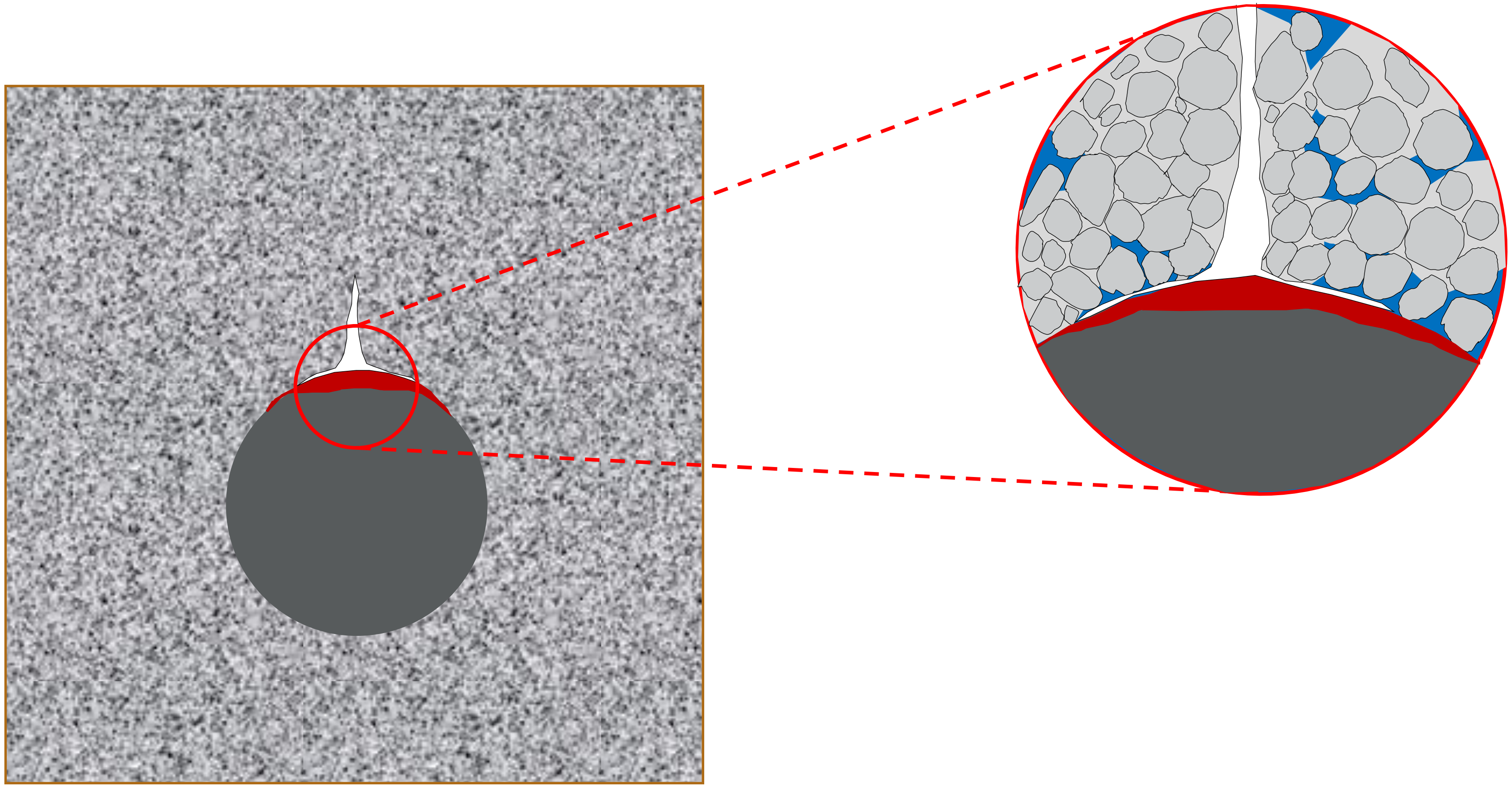
Service life model

Corrosion propagation



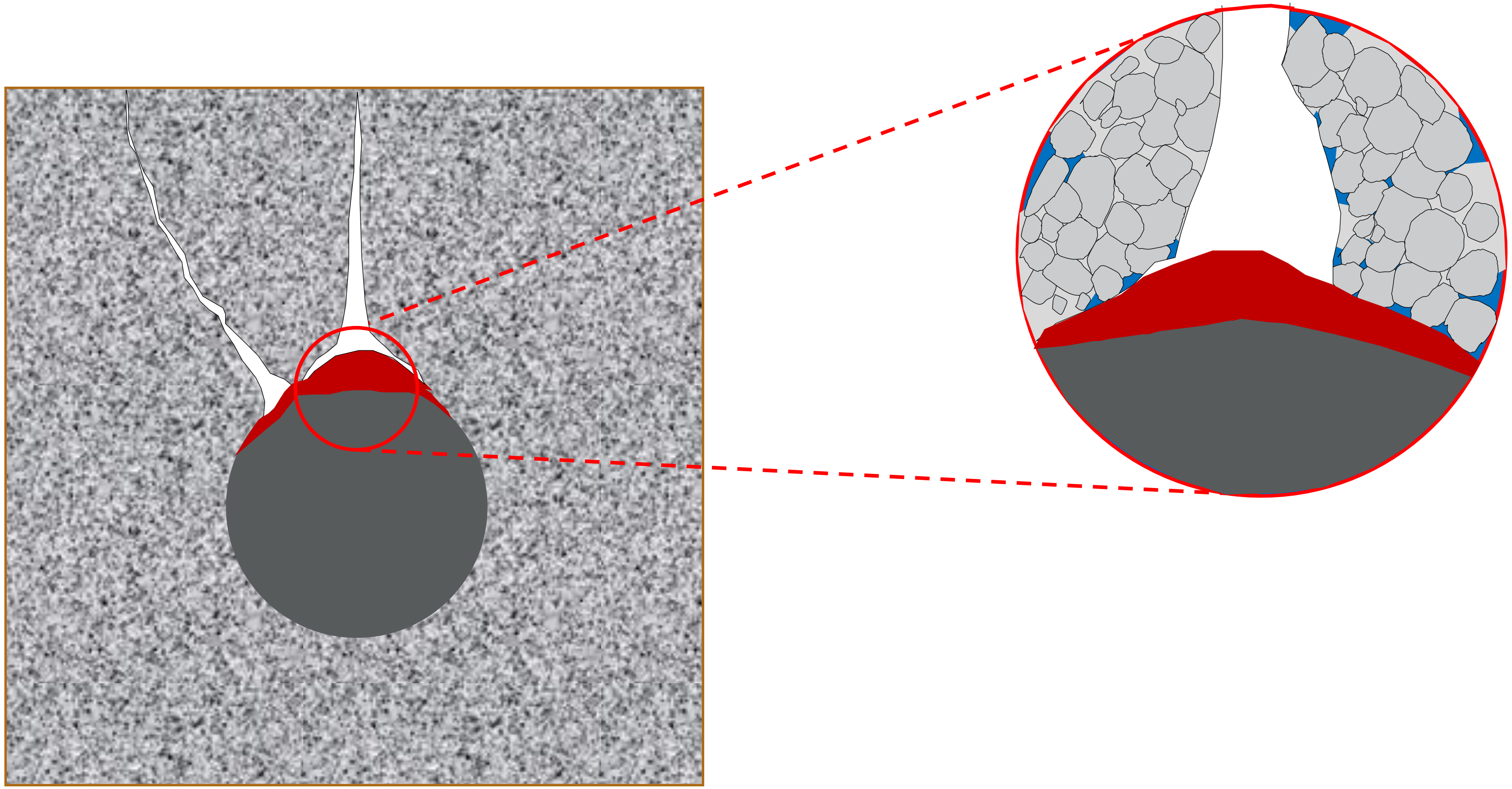
Service life model

Corrosion propagation

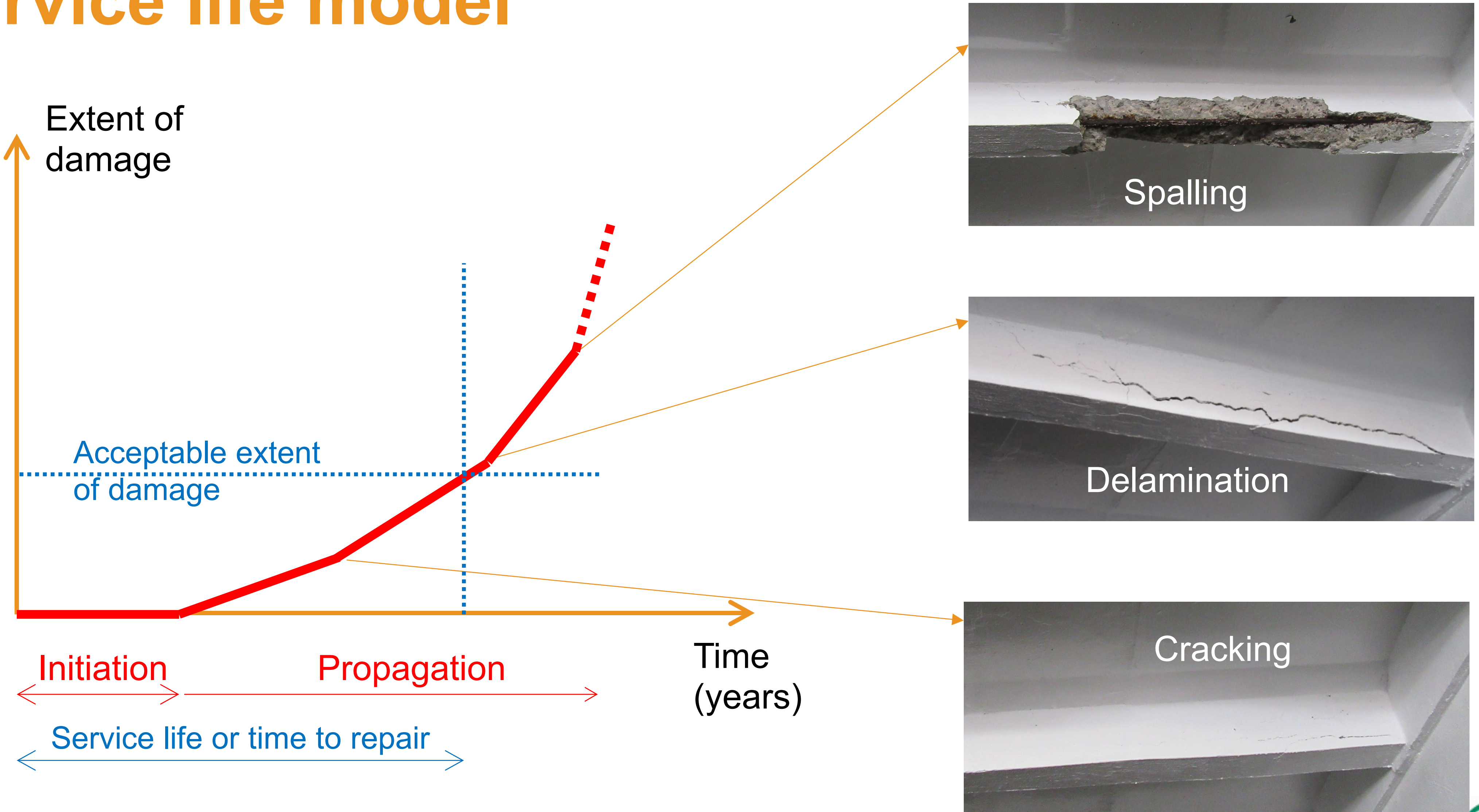


Service life model

Corrosion propagation



Service life model



Tuutti, K., 1982, Corrosion of Steel in Concrete, Swedish Cement and Concrete Research Institute, Stockholm, Sweden

Part III

Service life evaluation

Goal: provide a holistic assessment from limited data points

https://www.newyorker.com/cartoons/daily-cartoon/friday-june-29th-heres-your-problem

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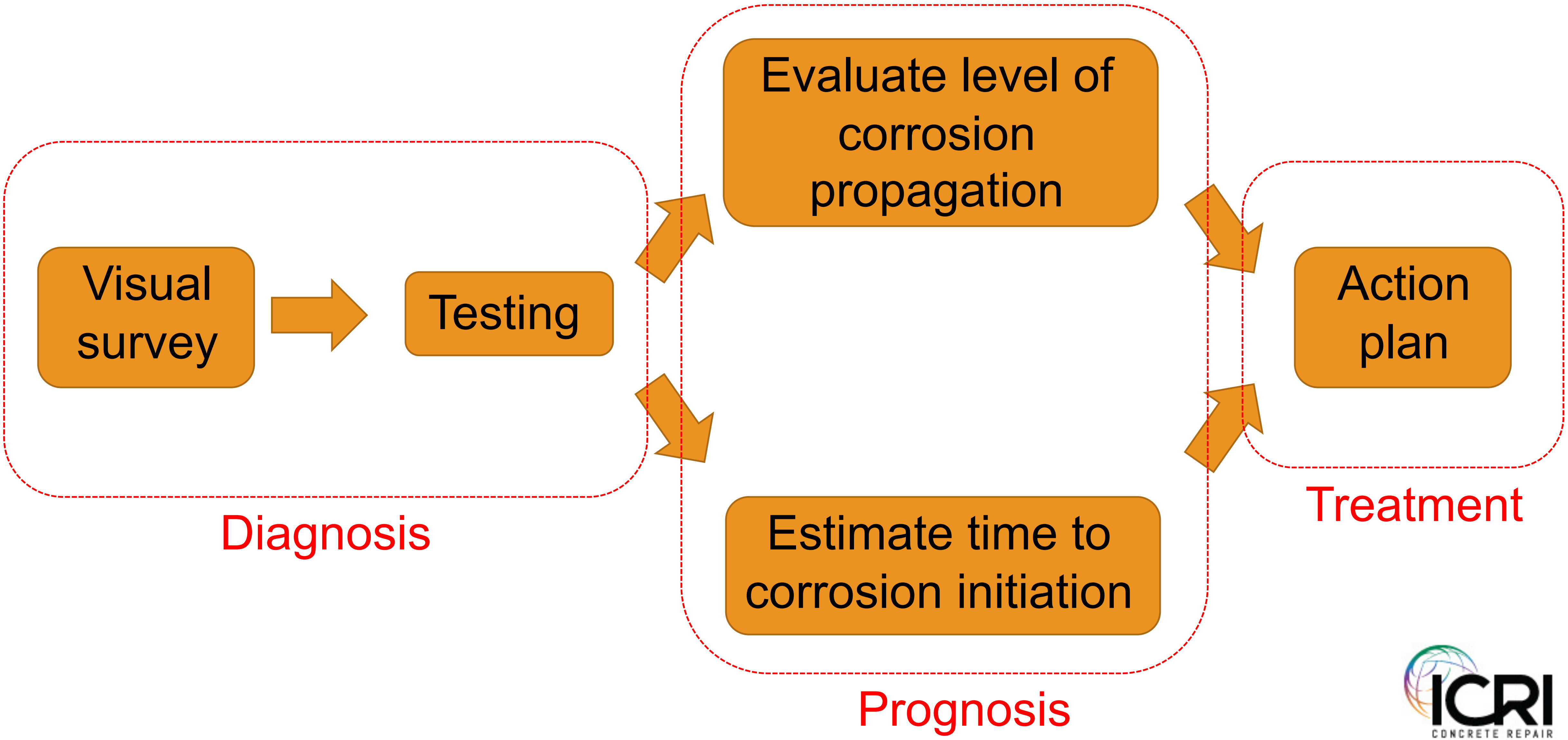
Service life evaluation

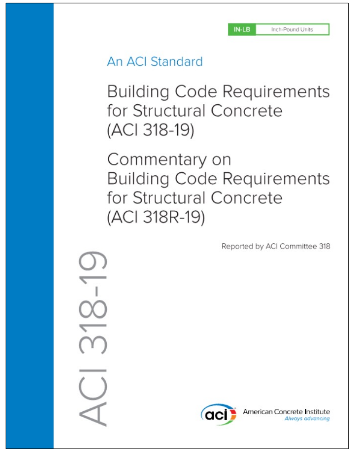


Service life evaluation

Materials

Environment

Design



Execution

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Diagnosis

Are there any sign of deterioration?

Diagnosis

Are there any construction defects?

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Diagnosis

What is the source of chlorides?

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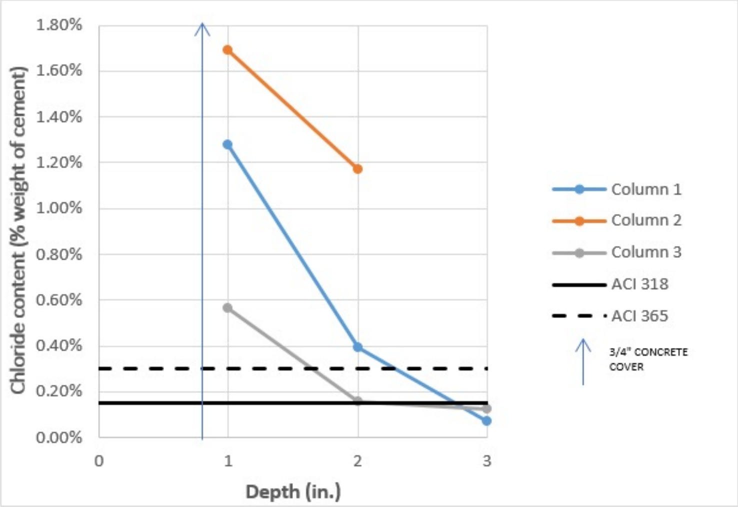
Diagnosis

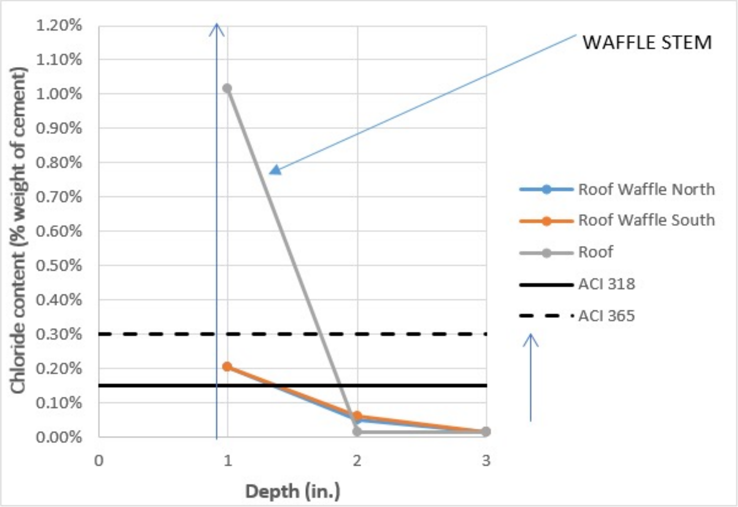
What type of protection do we have?

Diagnosis

Has corrosion initiated?

Test Location	Depth (in.)	Chloride content		
		Pounds of chlorides per cubic yard	Percent of concrete weight	Percent of cement weight
Column 1	1	7.67	0.202%	1.28%
	2	2.34	0.062%	0.39%
	3	0.42	0.011%	0.07%
Column 2	1	10.14	0.267%	1.69%
	2	7.01	0.184%	1.17%
	3	N/A		
Column 3	1	3.37	0.089%	0.56%
	2	0.93	0.024%	0.16%
	3	0.74	0.019%	0.12%
Roof Waffle North	1	1.23	0.032%	0.21%
	2	0.31	0.008%	0.05%
	3	0.10	0.003%	0.02%
Roof Waffle South	1	1.23	0.032%	0.21%
	2	0.36	0.009%	0.06%
	3	0.10	0.003%	0.02%
Roof	1	0.10	0.003%	0.02%
	2	0.10	0.003%	0.02%
	3	6.10	0.161%	1.02%





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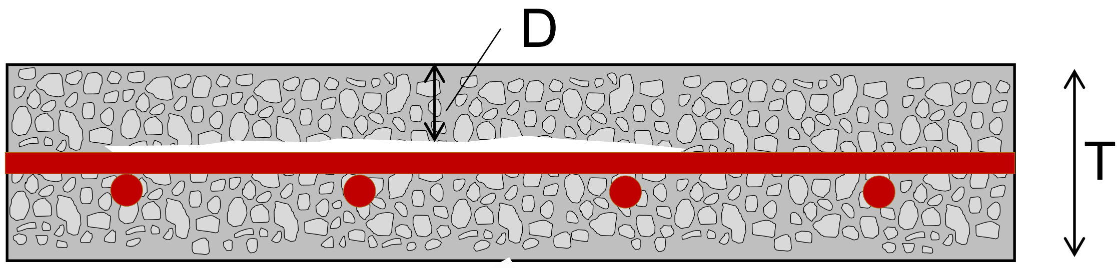
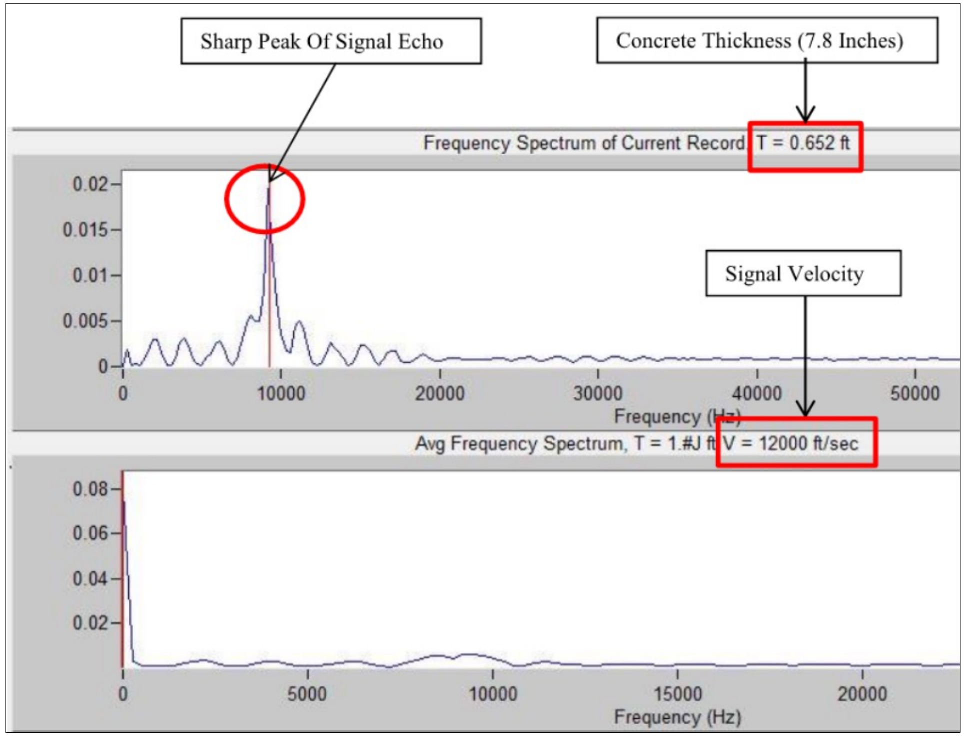
Diagnosis

Sounding and impact echo testing



ASTM D 4580

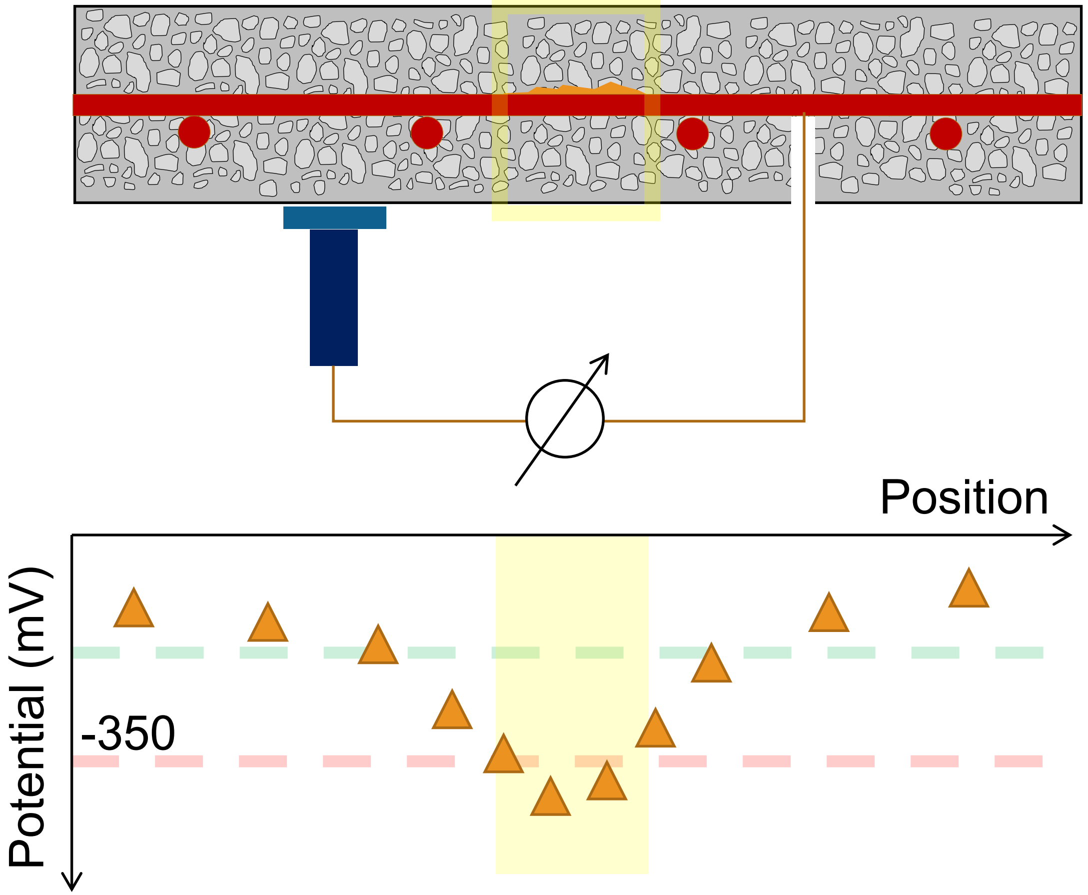
ASTM C 1383



Diagnosis

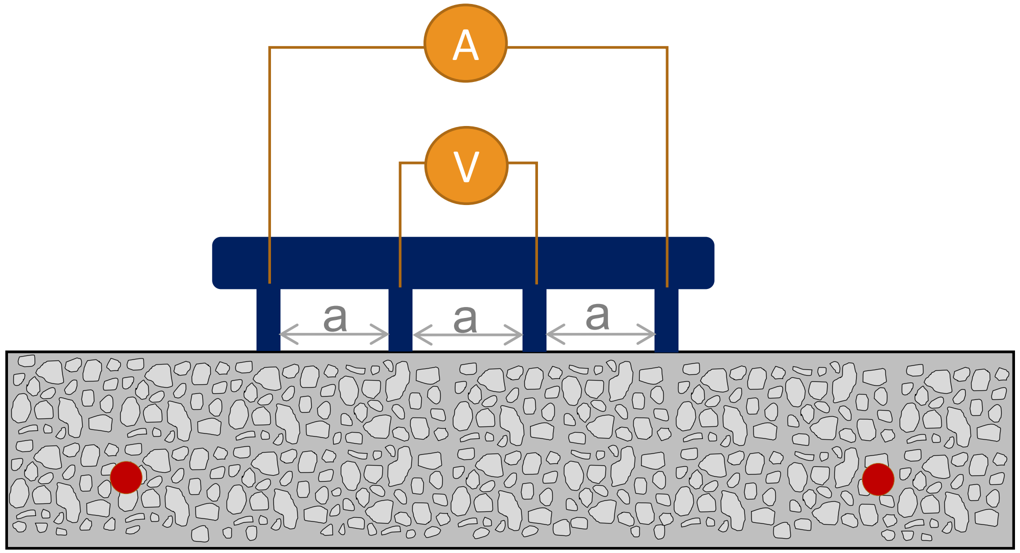
Half-cell potential testing

ASTM D 876

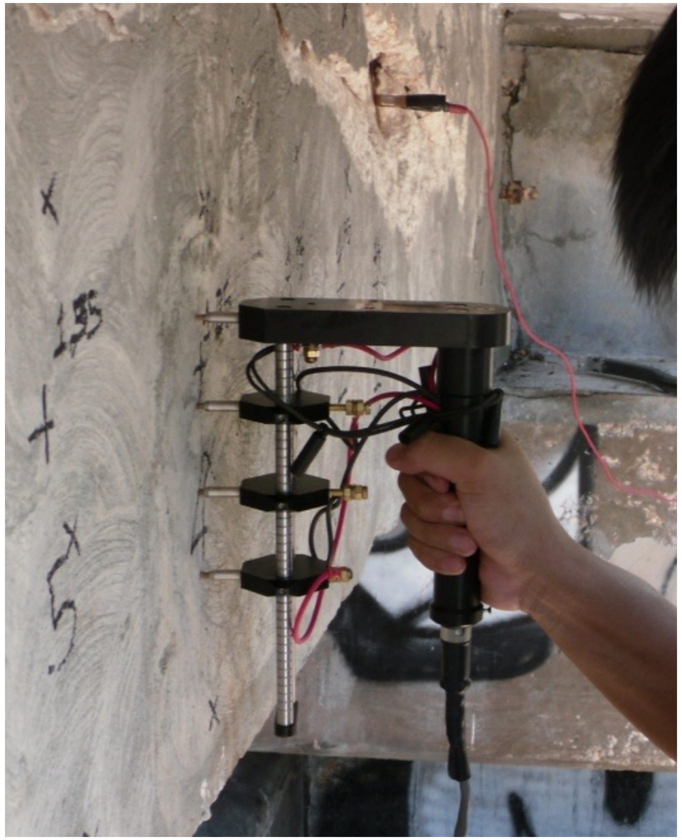


Diagnosis

Concrete electrical resistivity testing (Rilem, AASHTO)



Concrete resistivity (kΩ–cm)	Risk of corrosion
< 10	High
10 to 50	Moderate
50 to 100	Low
> 100	Negligible



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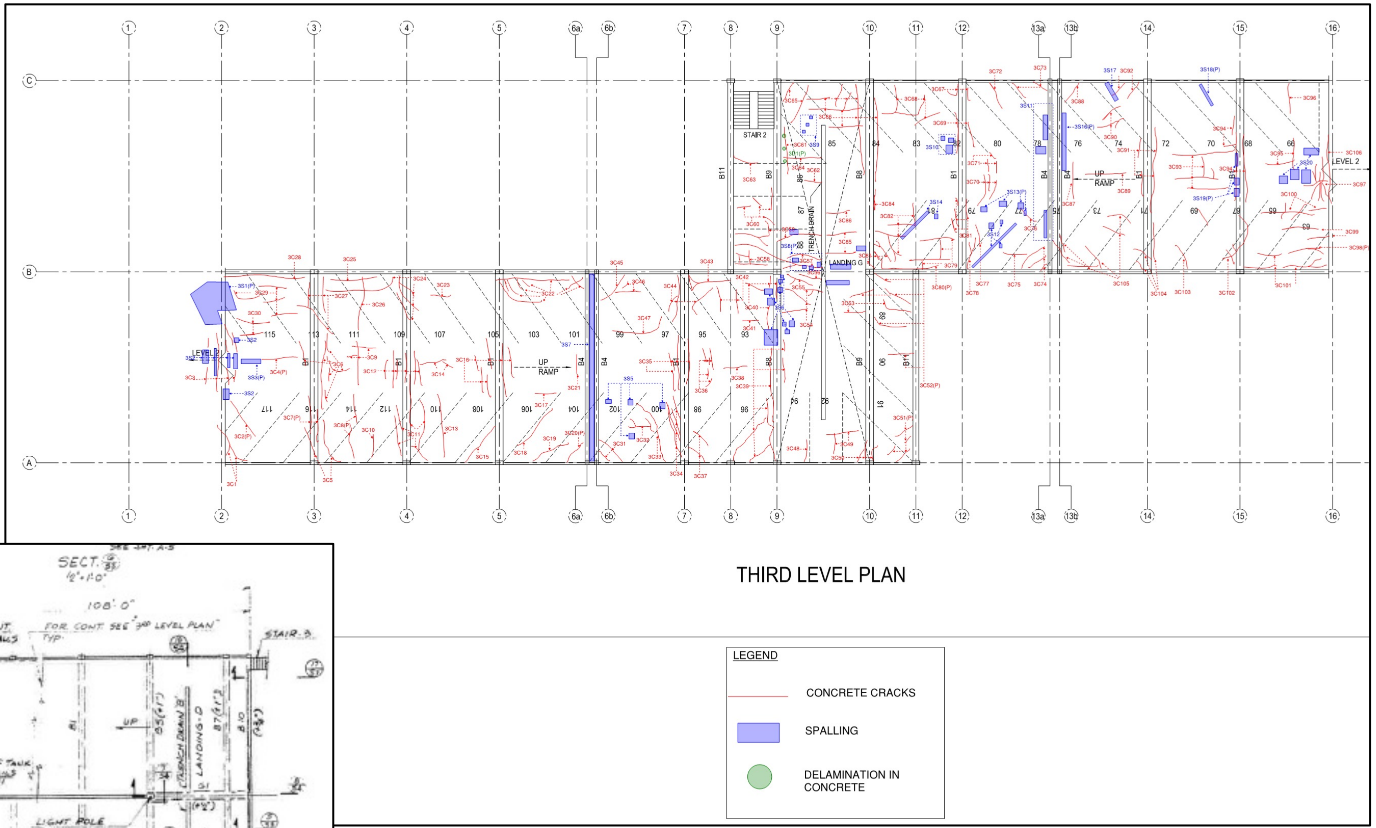
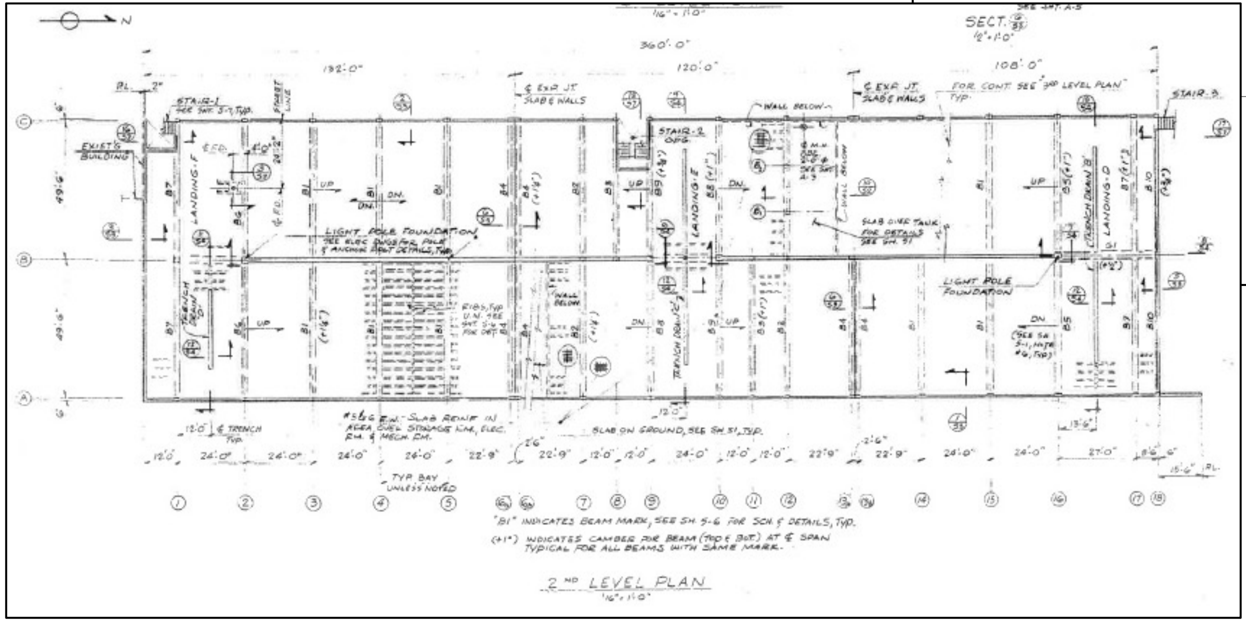
Diagnosis

Artificial intelligence, drones and laser scanning

Diagnosis

Damage mapping





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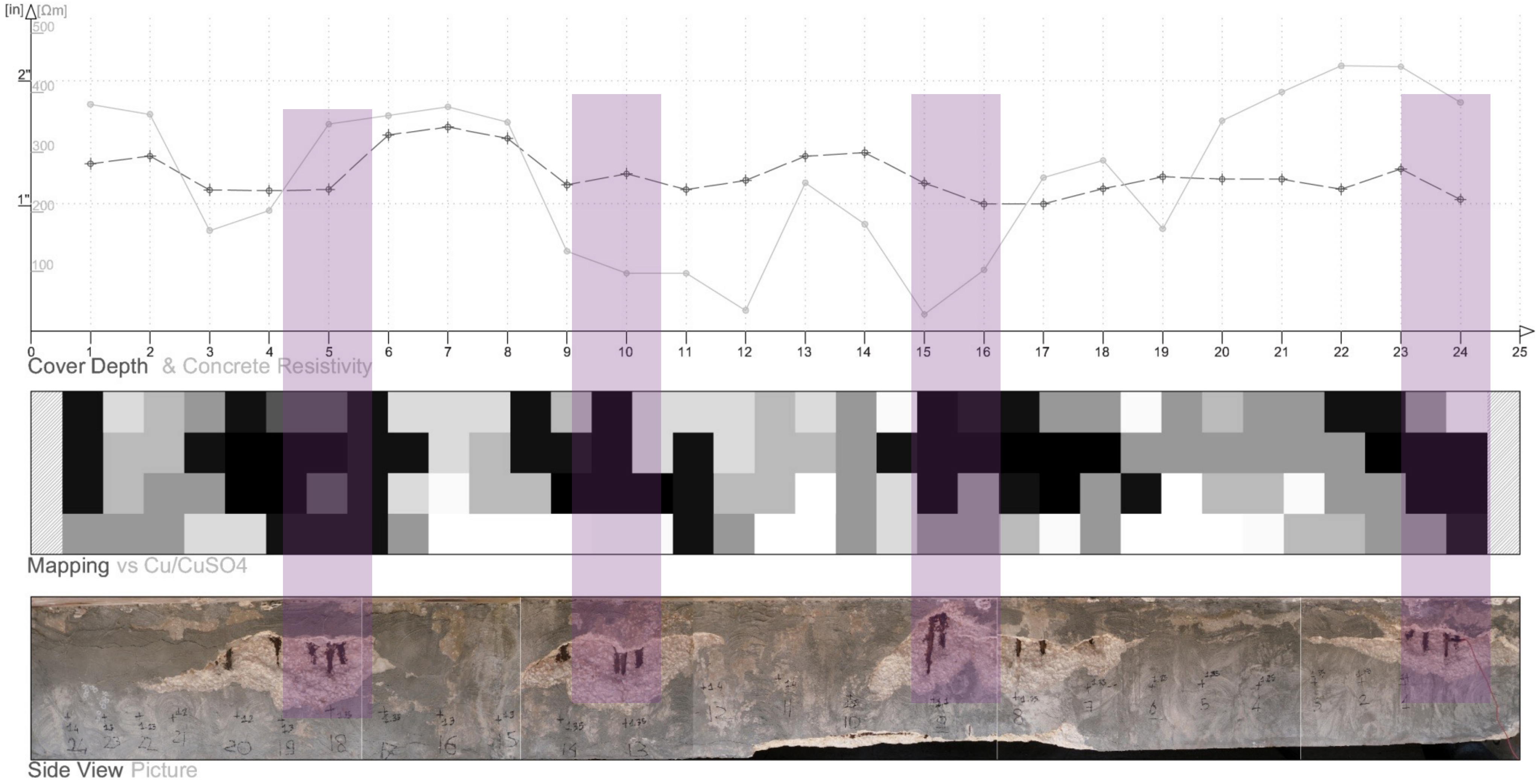
Diagnosis

Color-coded map of test results



Prognosis

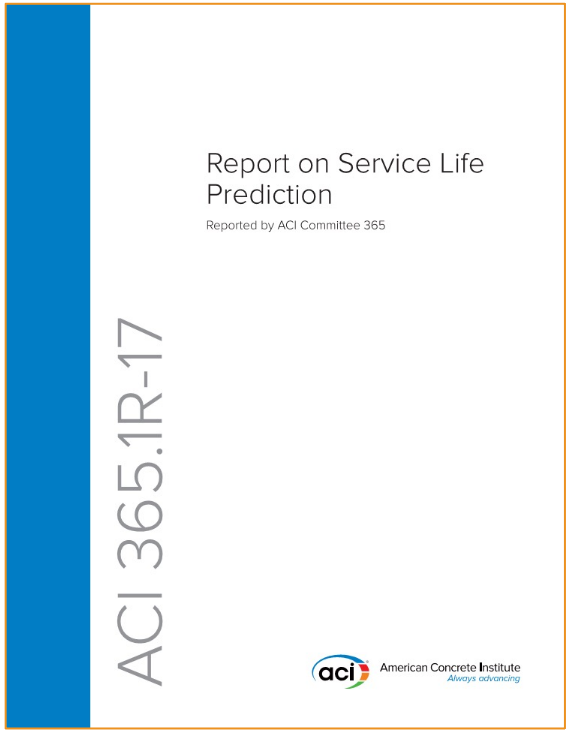
Corrosion initiation

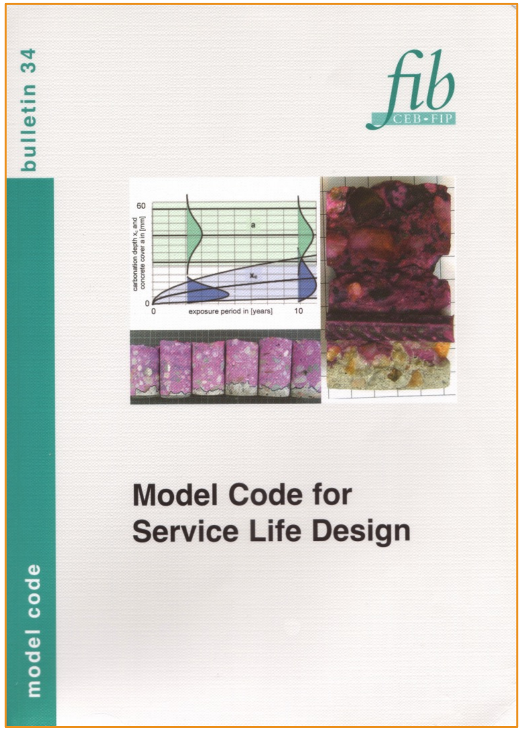
Environment

Geometric properties

$$C(x,t) = C_0\left(1 - erf\,\frac{x}{2\sqrt{D_t t}}\right)$$

Material properties





Prognosis

Corrosion initiation modeling

Environment

Geometric properties

$$C(x,t) = C_0\left(1 - erf\,\frac{x}{2\sqrt{D_t t}}\right)$$

Material properties

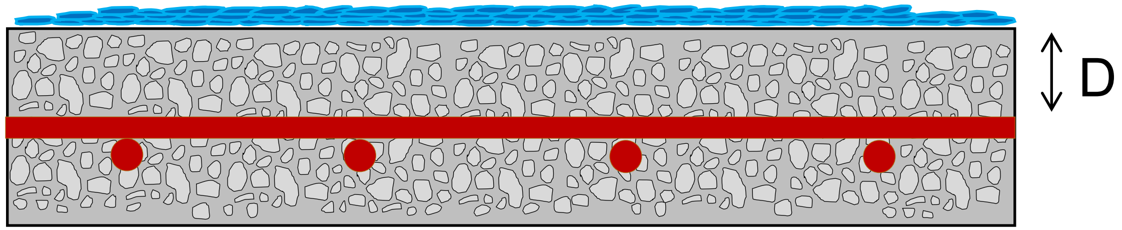
TABLE 1. INPUTS COMPARISON OF SERVICE LIFE PREDICTION MODELS

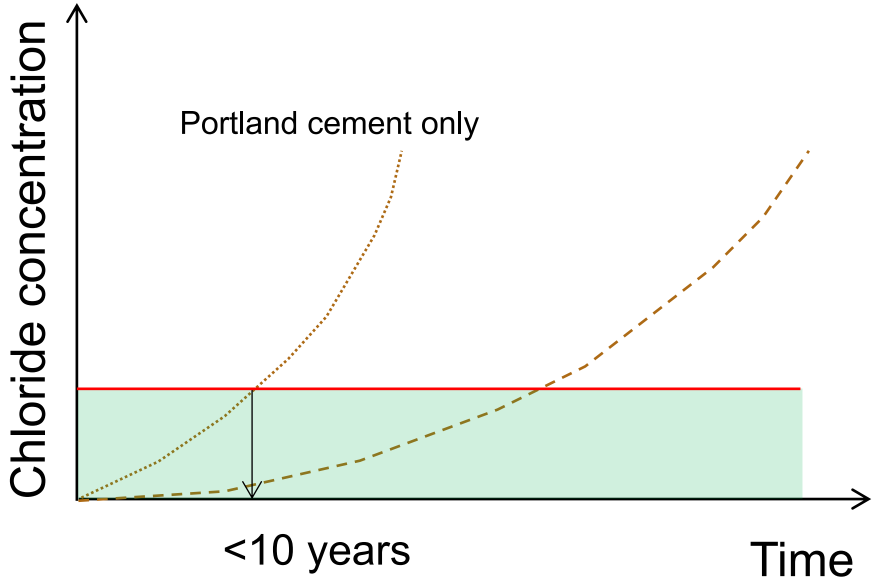
	Life-365	STADIUM	ConcreteWorks	DURACRETE	CHLODIF	ClinConc	NIST CIKS	NCHRP 558
Chloride binding coefficient		✓	✓			✓	✓	
Carbonation		✓		✓				
Temperature	✓	✓	✓	✓	✓	✓	✓	✓
Relative Humidity		✓	✓	✓	✓			
Corrosion inhibitor content	✓	✓	✓					
Type of steel	✓	✓						
Admixture in concrete	✓	✓	✓	✓	✓	✓	✓	
Porosity		✓				✓	✓	
Cement composition		✓	✓				✓	
Geographic location	✓		✓					
Type of structure	✓							
Effect of co-existing ions		✓	✓			✓		

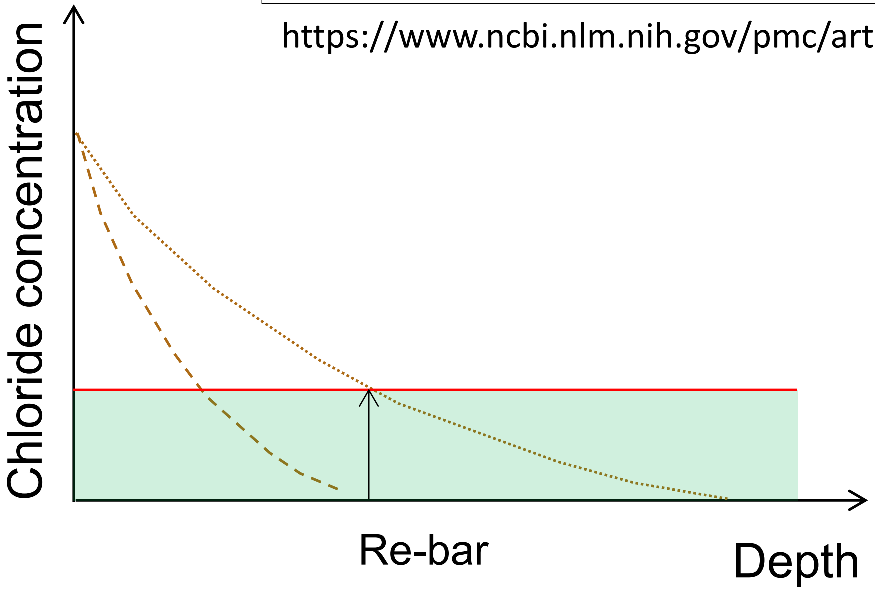
Modeling Corrosion-Related Service Life of Existing Concrete Materials Performance Magazine October 2019 (bluetoad.com)

Prognosis

Time to corrosion initiation







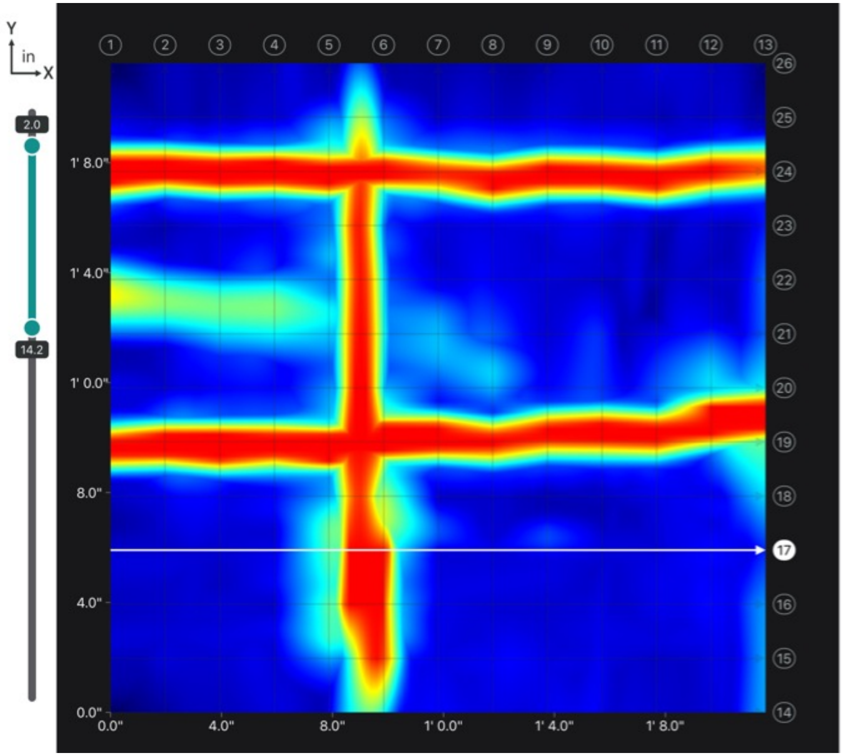
Surface chloride concentration

Source	Wave Splashing Zone	Coastal Atmospheric Zone	Offshore Atmospheric Zone
ACI-365	18.4	23(2.3) [1]	13.8(0.92) [1]
JSCE	14.95	10.35	2.3
DuraCrete	12.42	4.11	4.11
GB/T51355-2019	17	11.5	2.57
Bamforth	18	12	6
McGee	-	2.95	1.69

https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7288091/

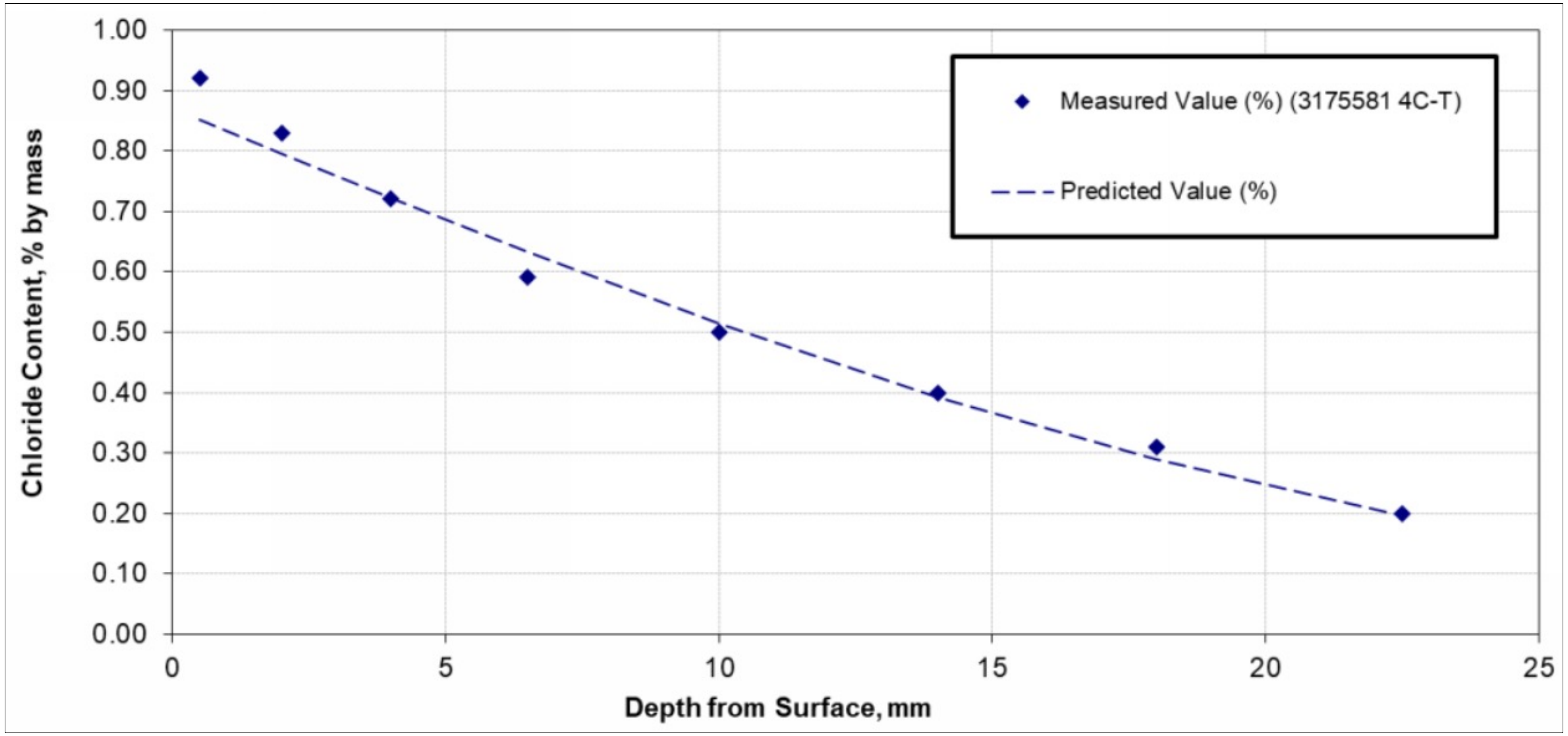
Prognosis

Ground penetrating radar (ASTM, AASHTO, ACI)



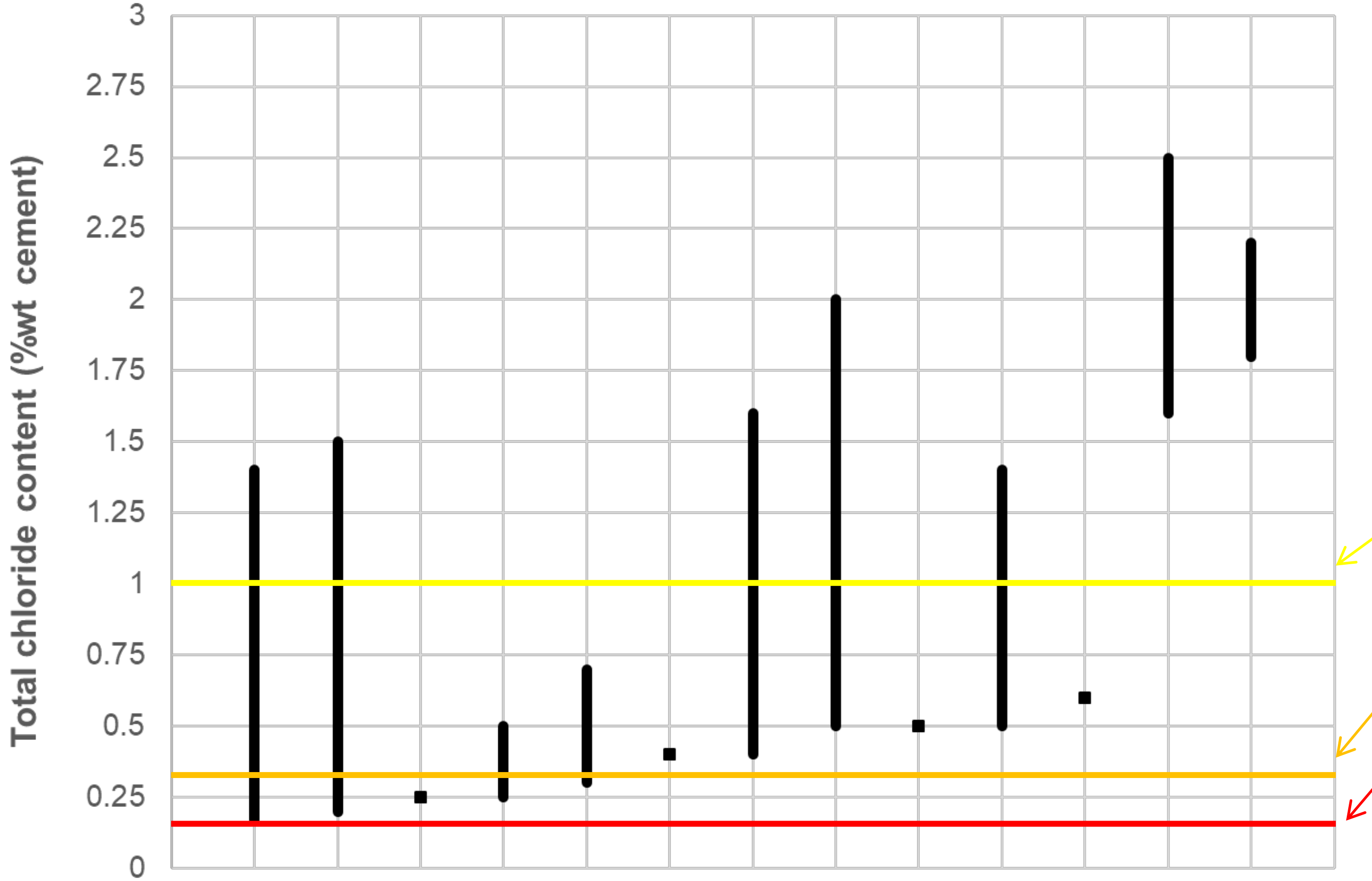
Prognosis

Concrete apparent diffusivity (ASTM C 1556)



Prognosis

Chloride content threshold



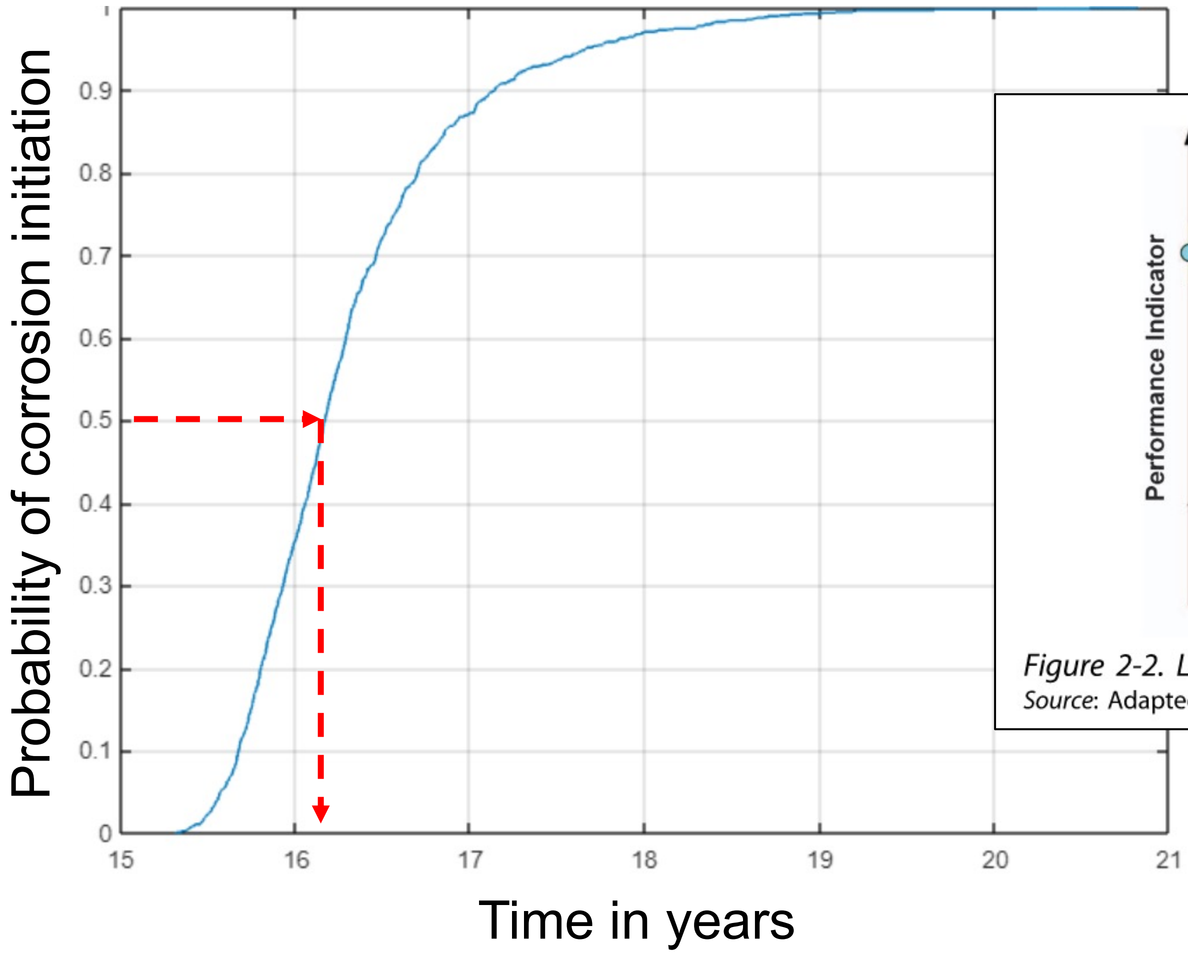
https://www.germann.org/TestSystems/RCT%20&%20RCTW/rct_3.6.pdf

ACI 318 chloride limits:

- Exposure class C0
- Exposure class C1
- Exposure class C2

Prognosis

Probabilistic analysis



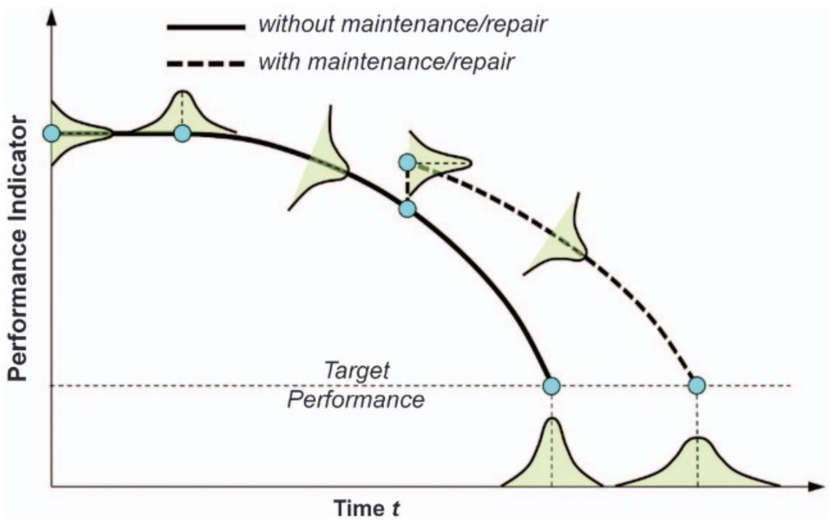
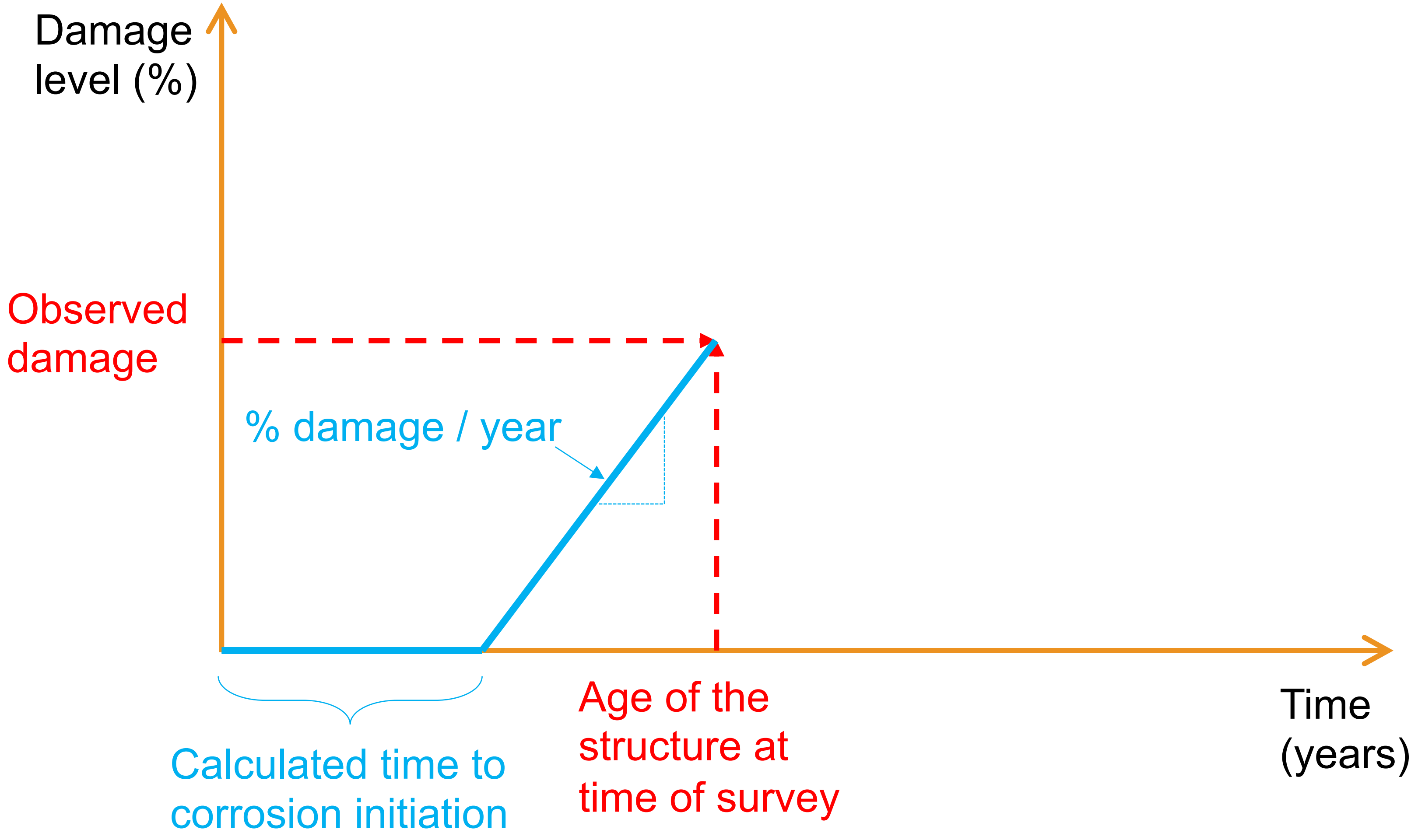


Figure 2-2. Life-cycle performance profile under uncertainty.
Source: Adapted from Biondini and Frangopol (2016).

(Biodini and Frangopol, 2020)

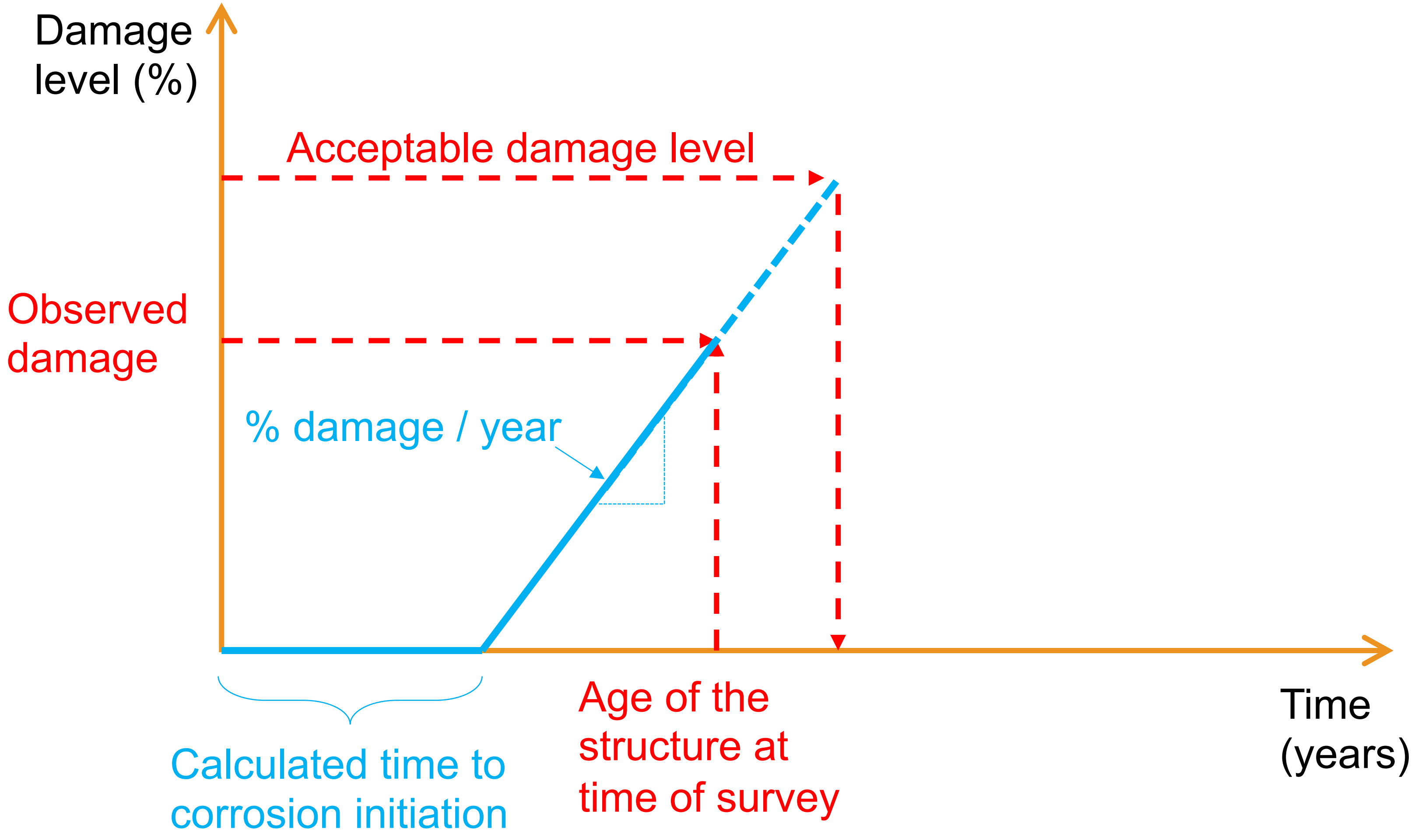
Prognosis

Evaluation of residual service life



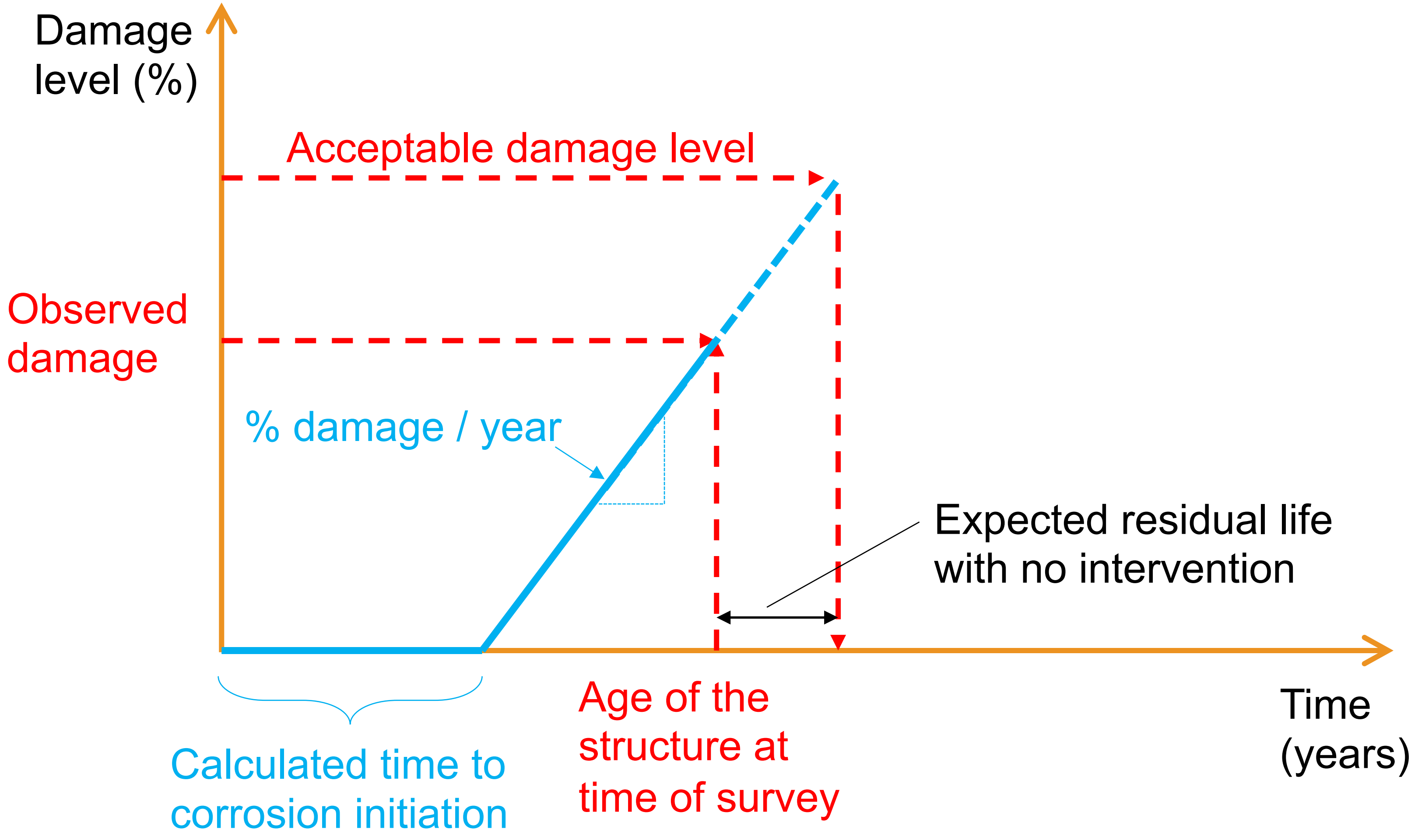
Prognosis

Evaluation of residual service life



Prognosis

Evaluation of residual service life



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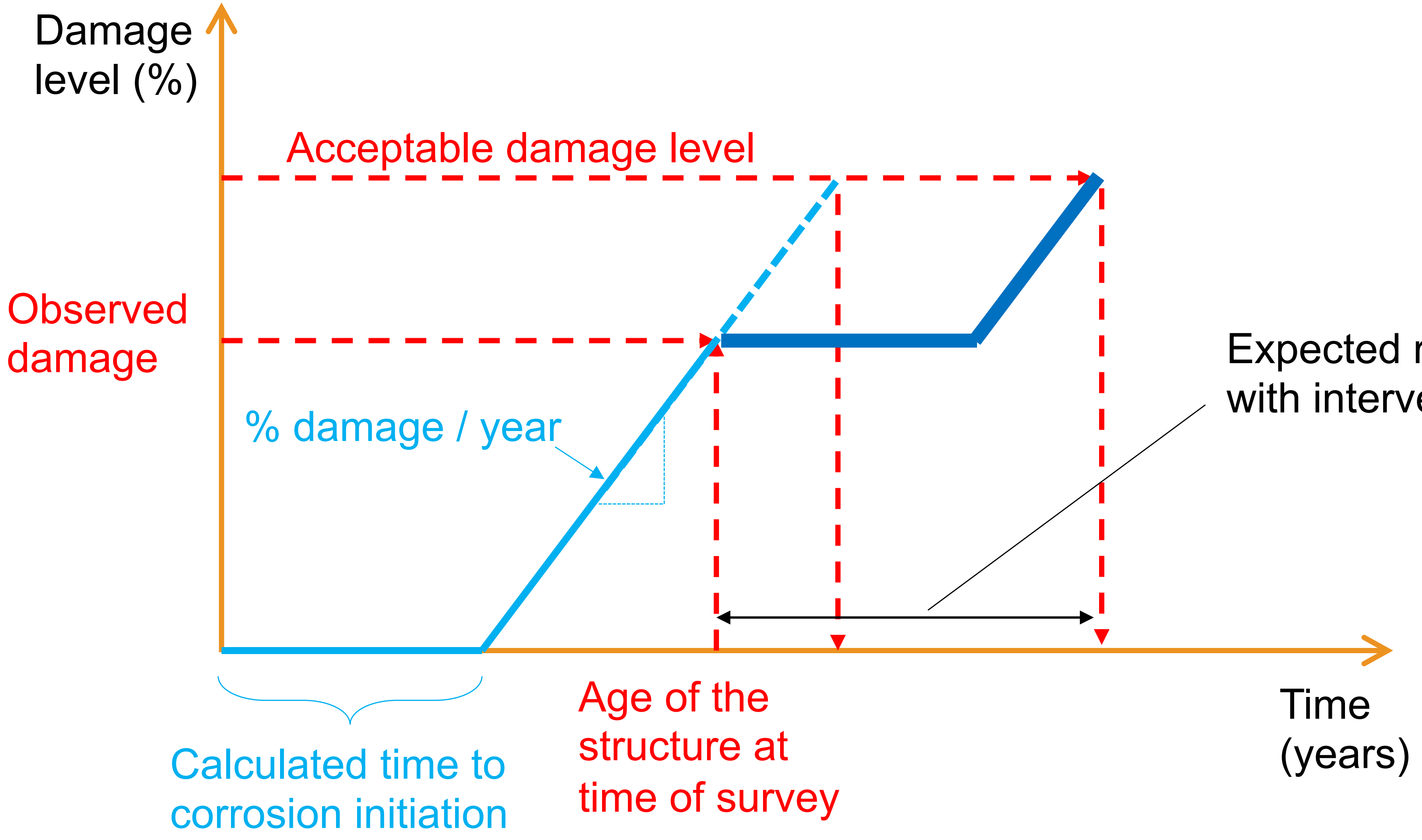
Evaluation of residual service life



Prognosis

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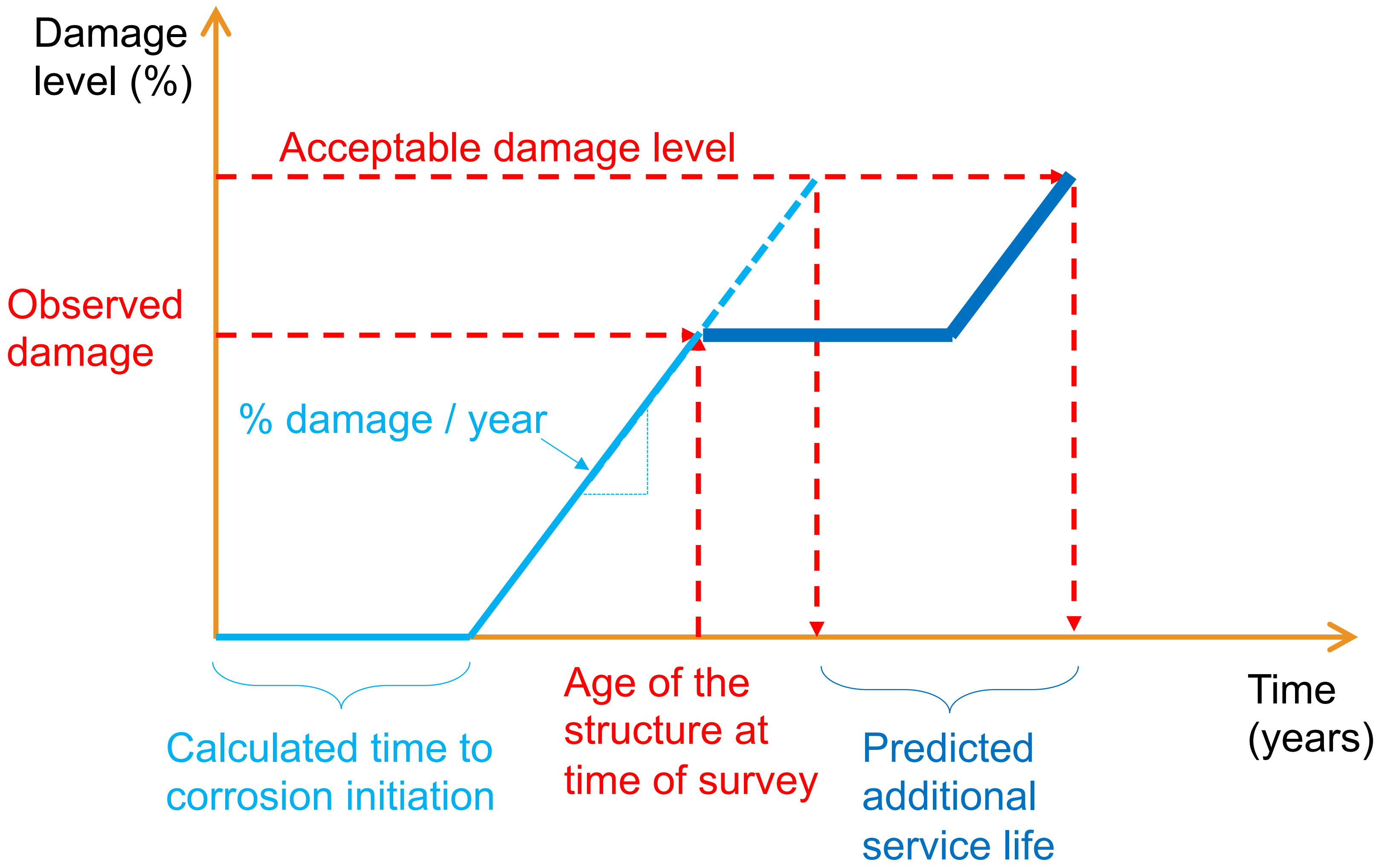

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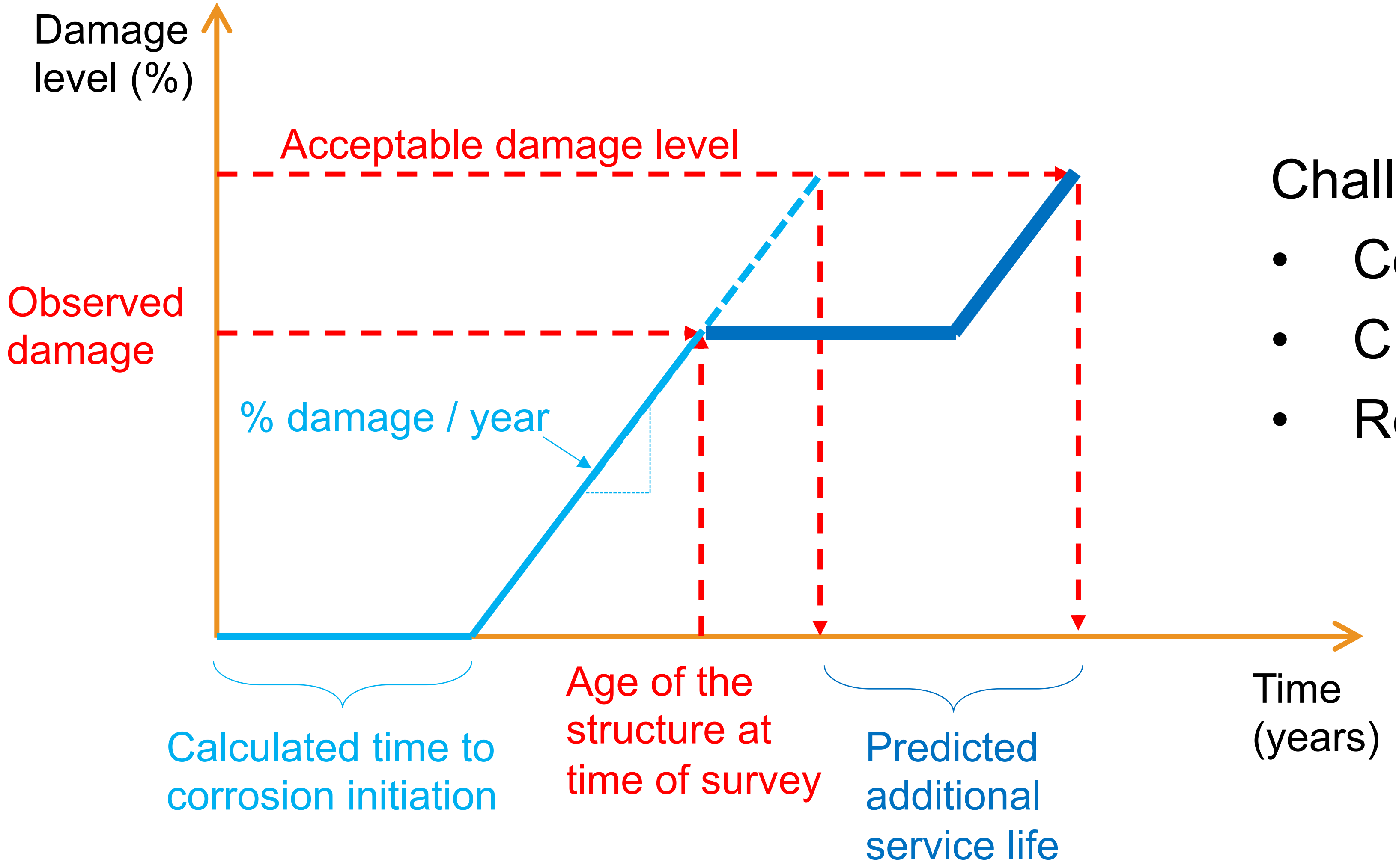

Challenges:

- Coatings
- Cracking
- Repairs

Part IV

What's next?

Public Law No: 117-58 (11/15/2021)

Infrastructure Investment and Jobs Act

Among other provisions, this bill provides new funding for infrastructure projects, including for

- roads, bridges, and major projects;
- passenger and freight rail;
- highway and pedestrian safety;
- public transit;
- broadband;
- ports and waterways;
- airports;
- water infrastructure;
- power and grid reliability and resiliency;
- resiliency, including funding for coastal resiliency, ecosystem restoration, and weatherization;
- clean school buses and ferries;
- electric vehicle charging;
- addressing legacy pollution by cleaning up Brownfield and Superfund sites and reclaiming abandoned mines; and
- Western Water Infrastructure.

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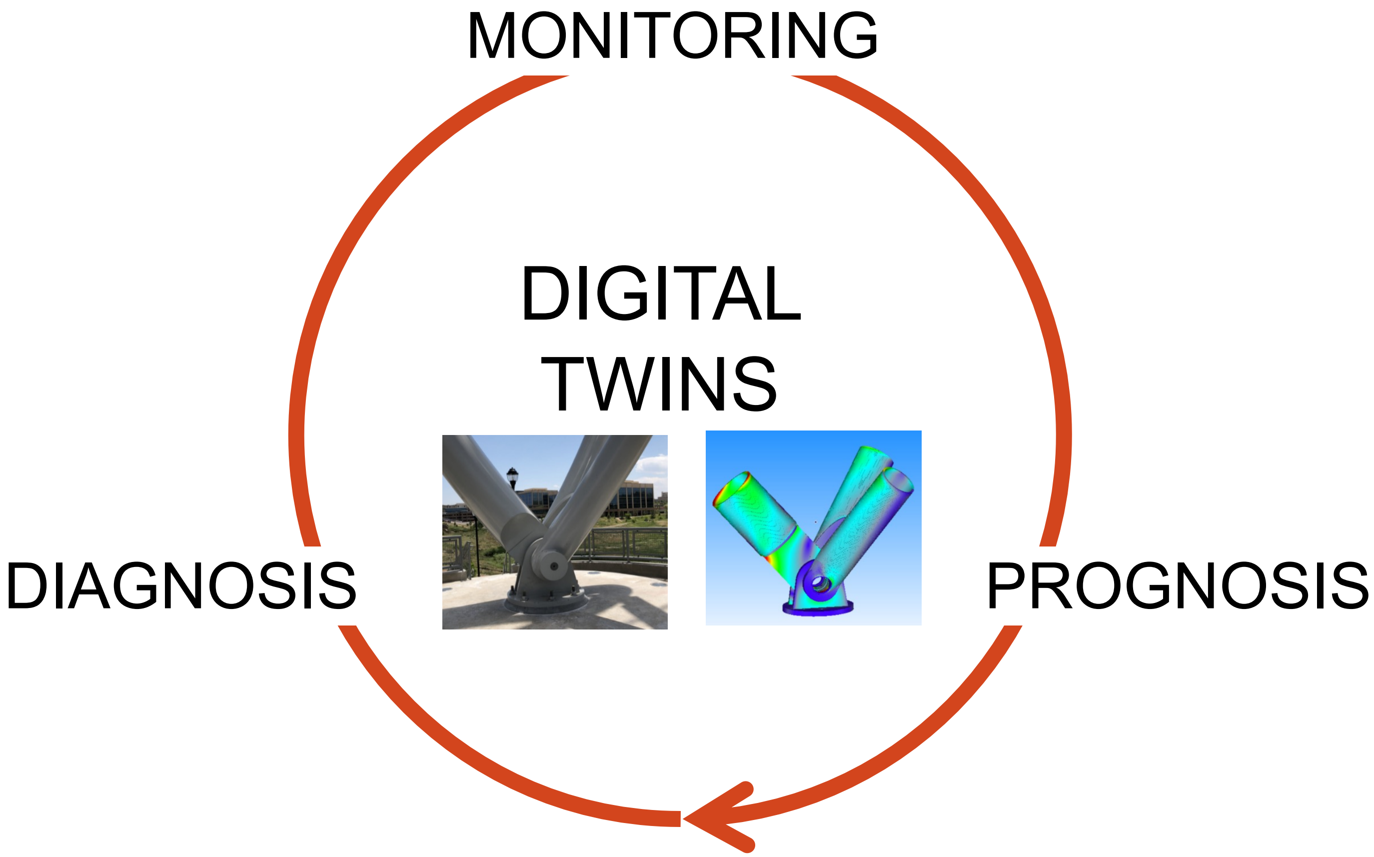
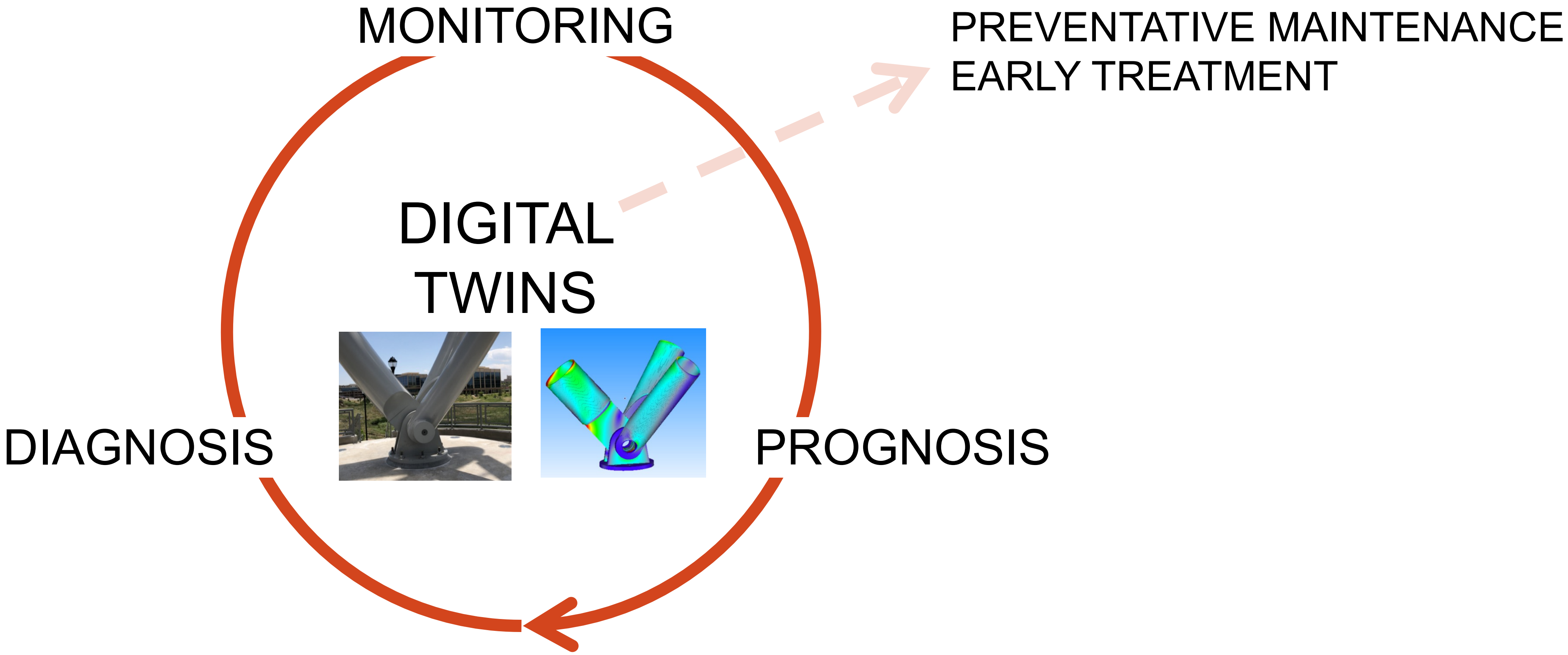
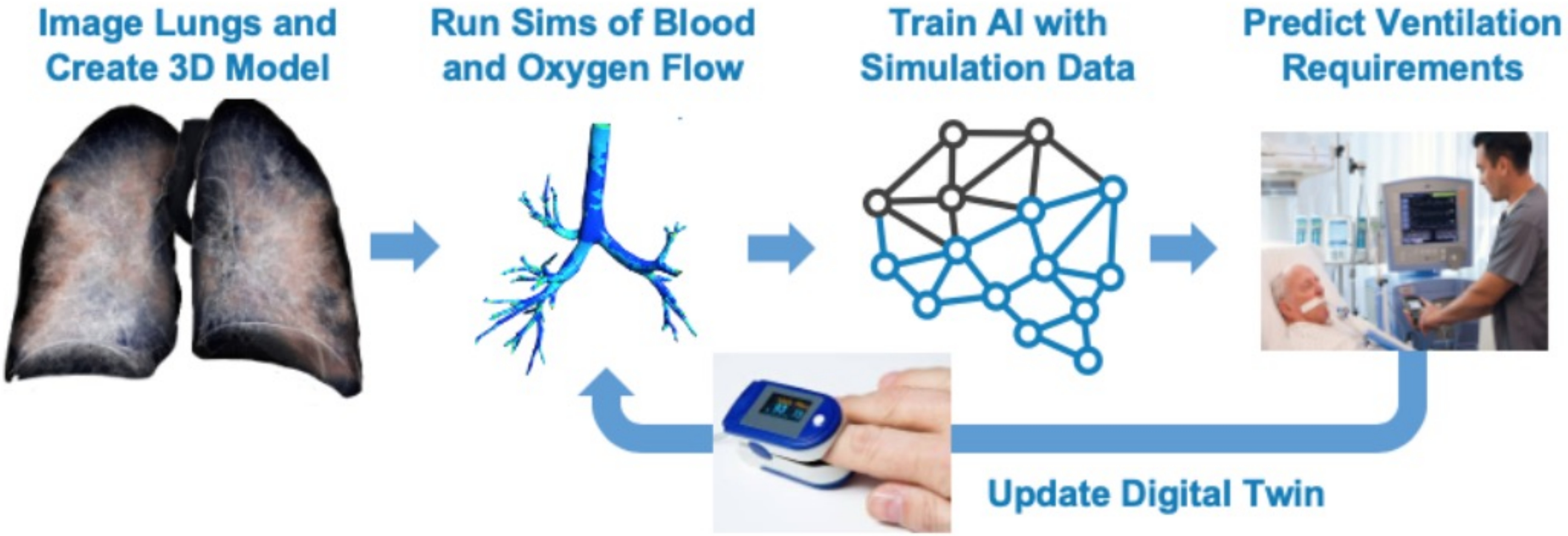
Big picture goal



Big picture goal

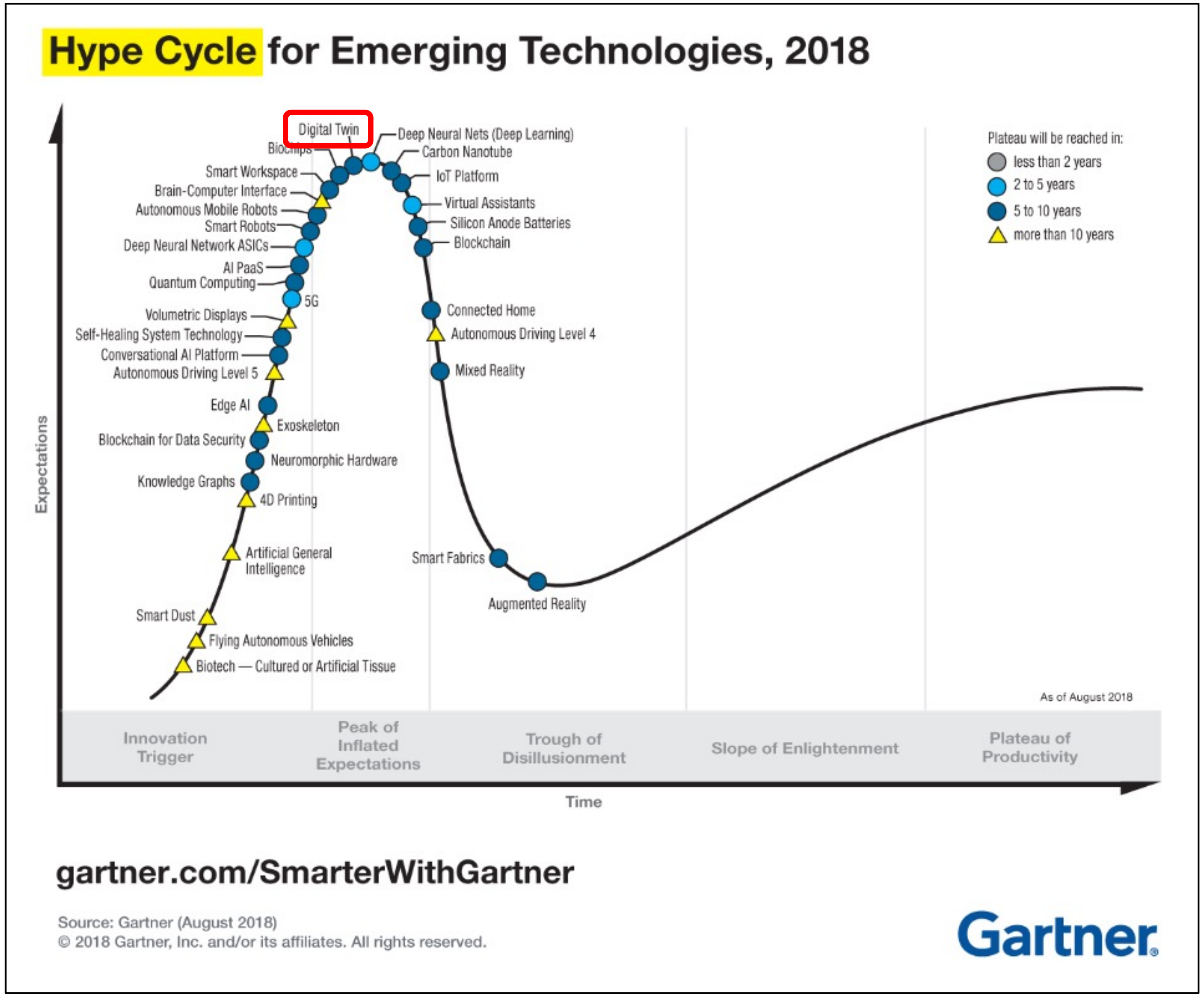


Digital twins

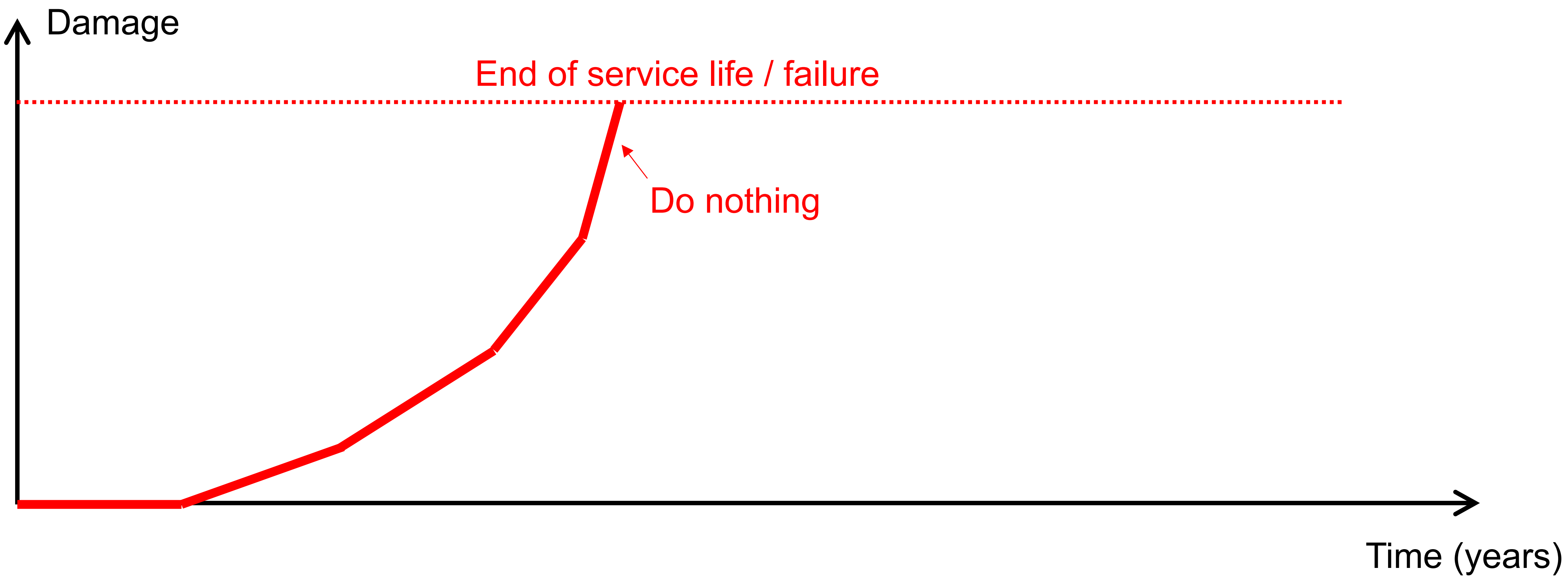


https://www.ttwiin.com/news/onscale-launches-project-breatheasy-digital-twins-of-lungs-to-improve-covid-19-patients-outcomes

Digital twins



Preventative maintenance



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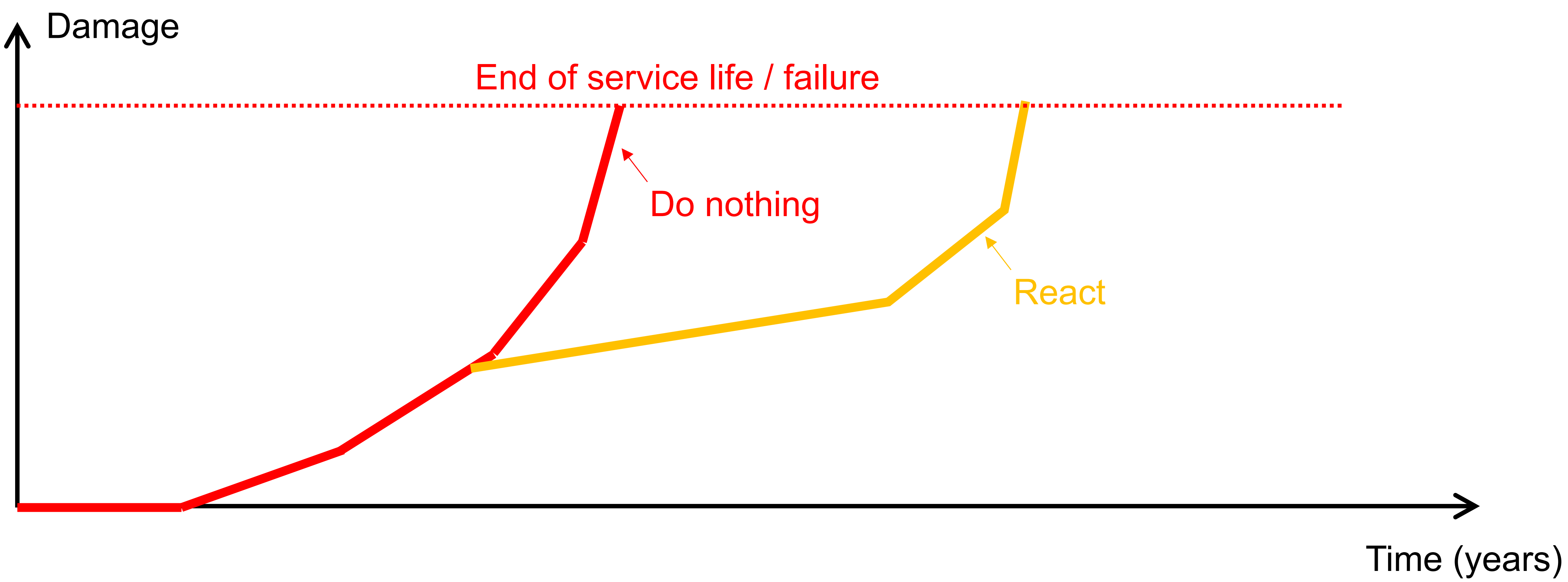

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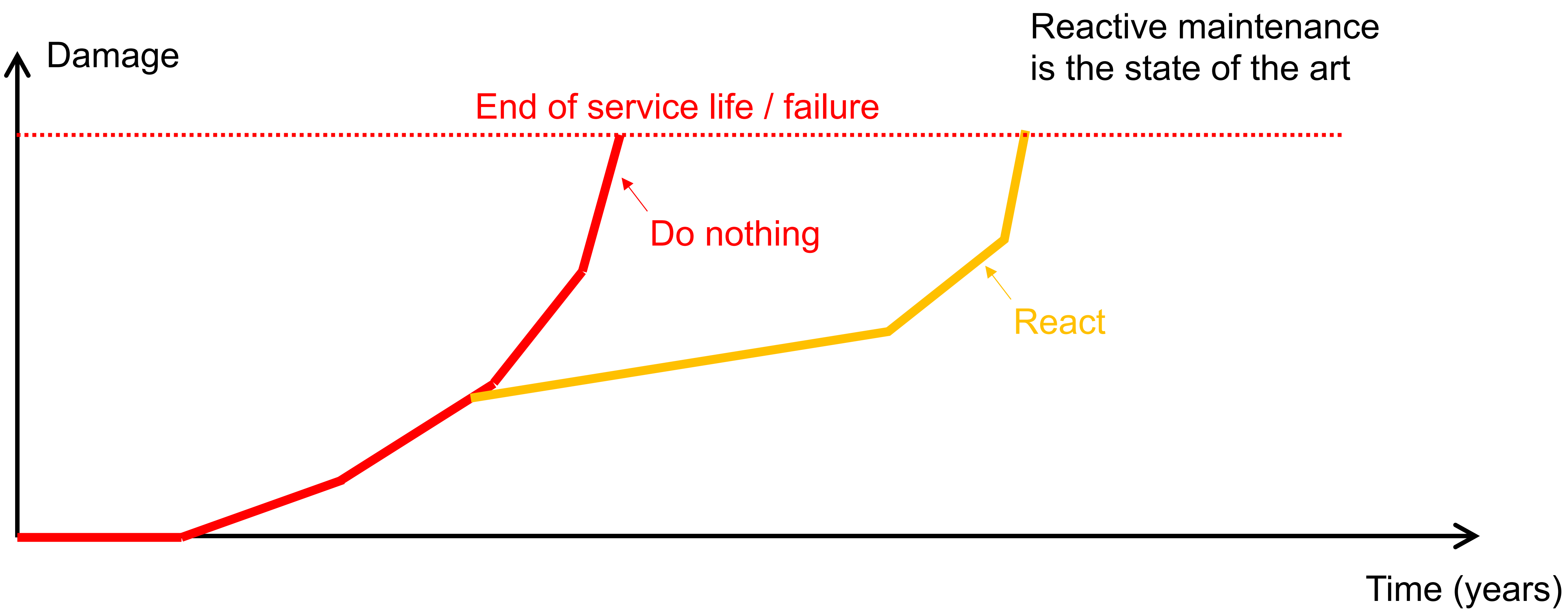
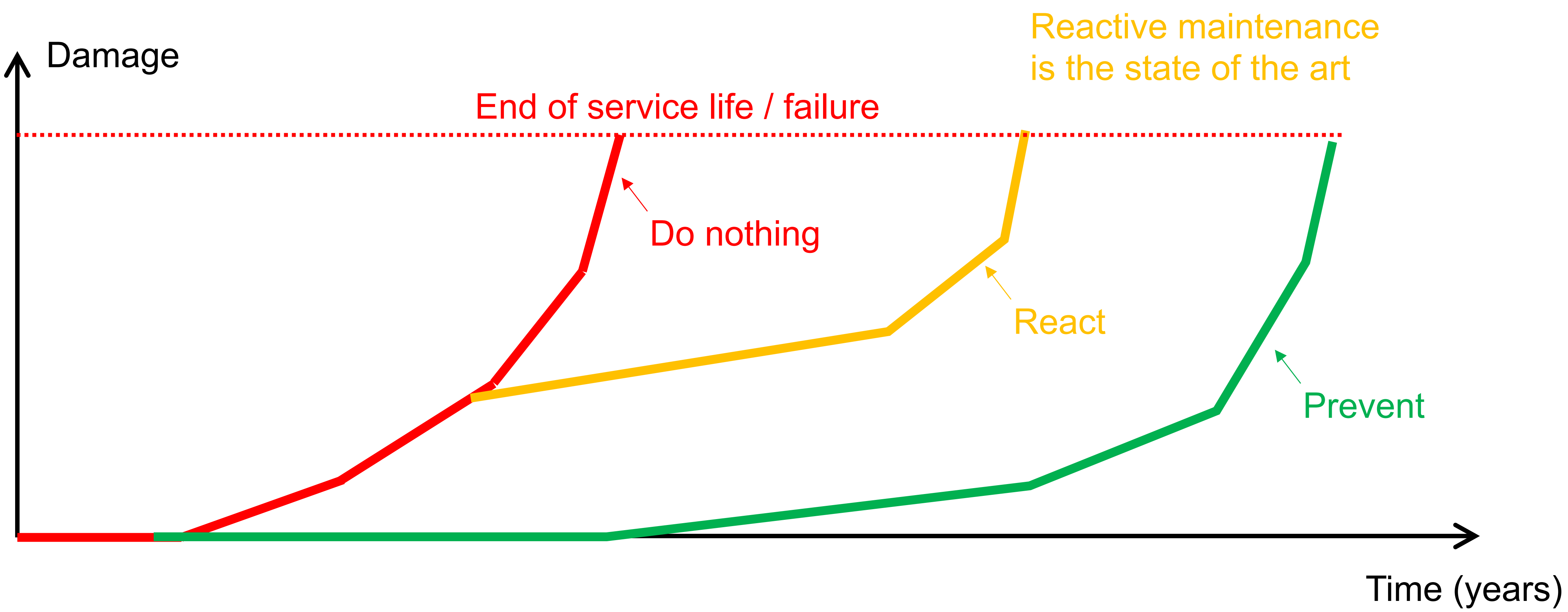
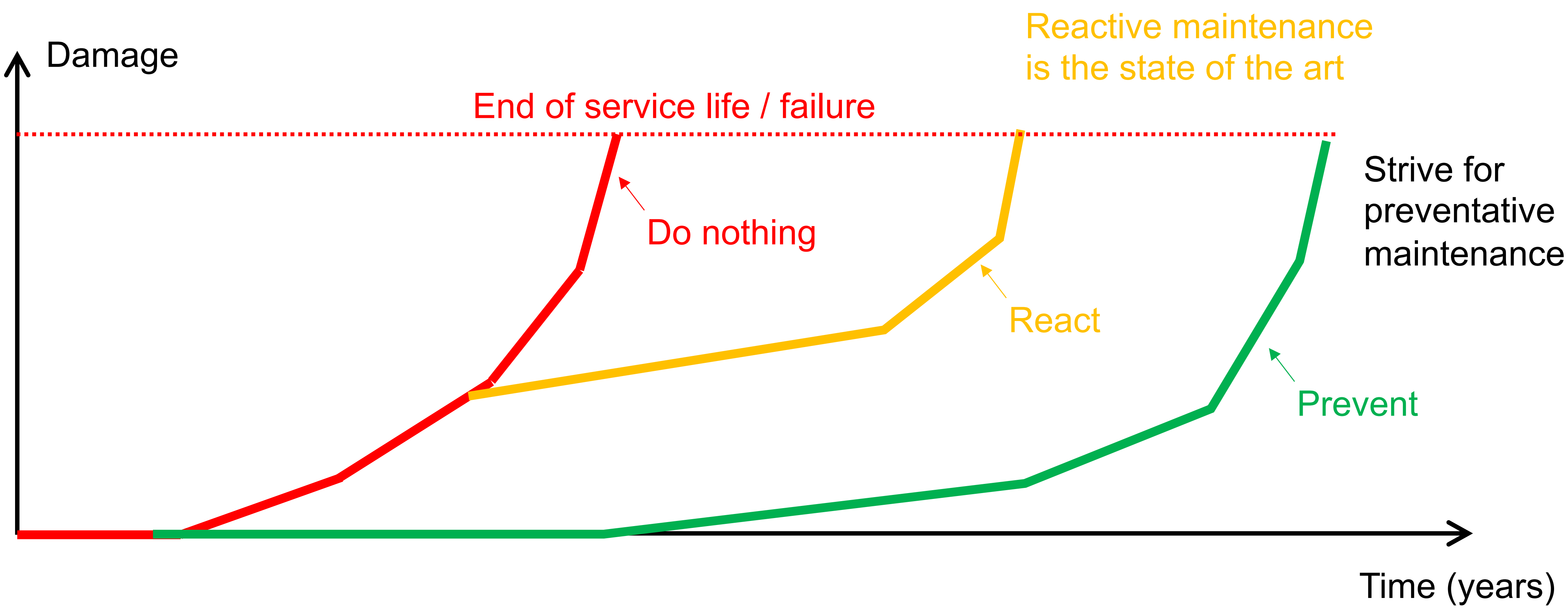


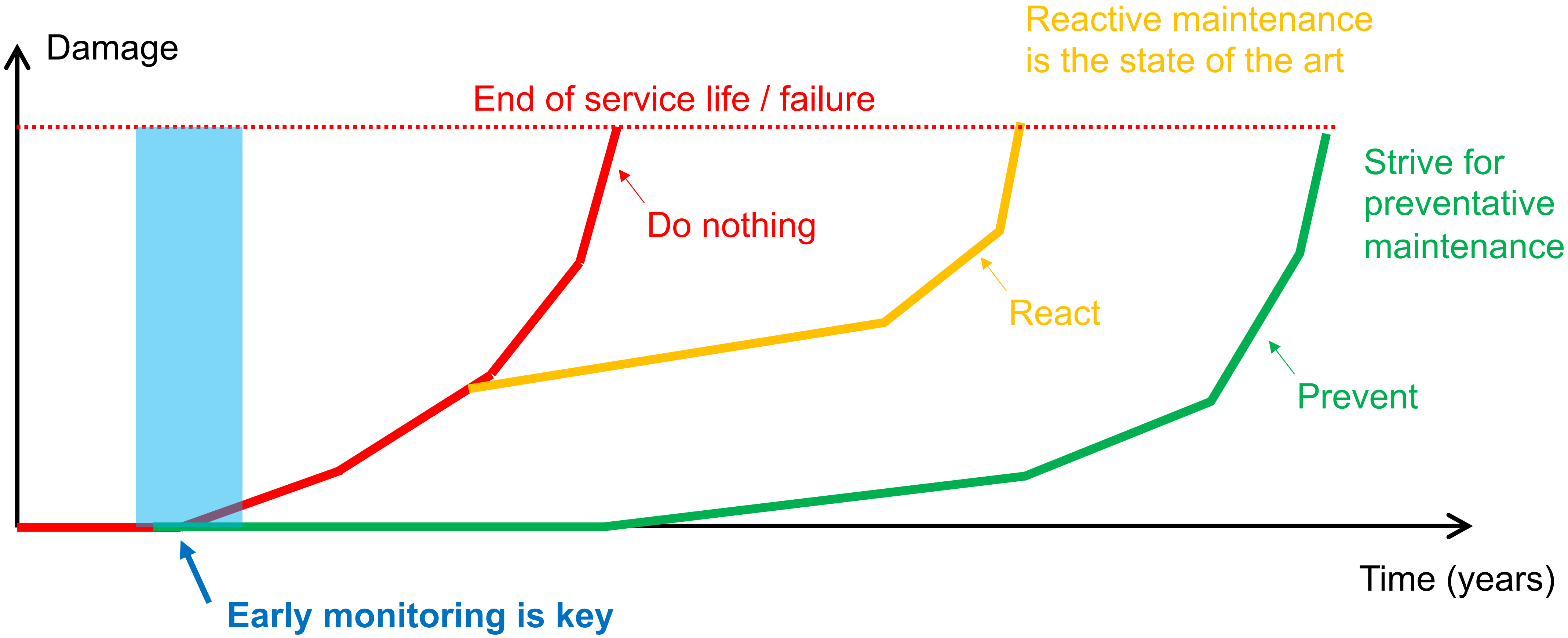
Preventative maintenance



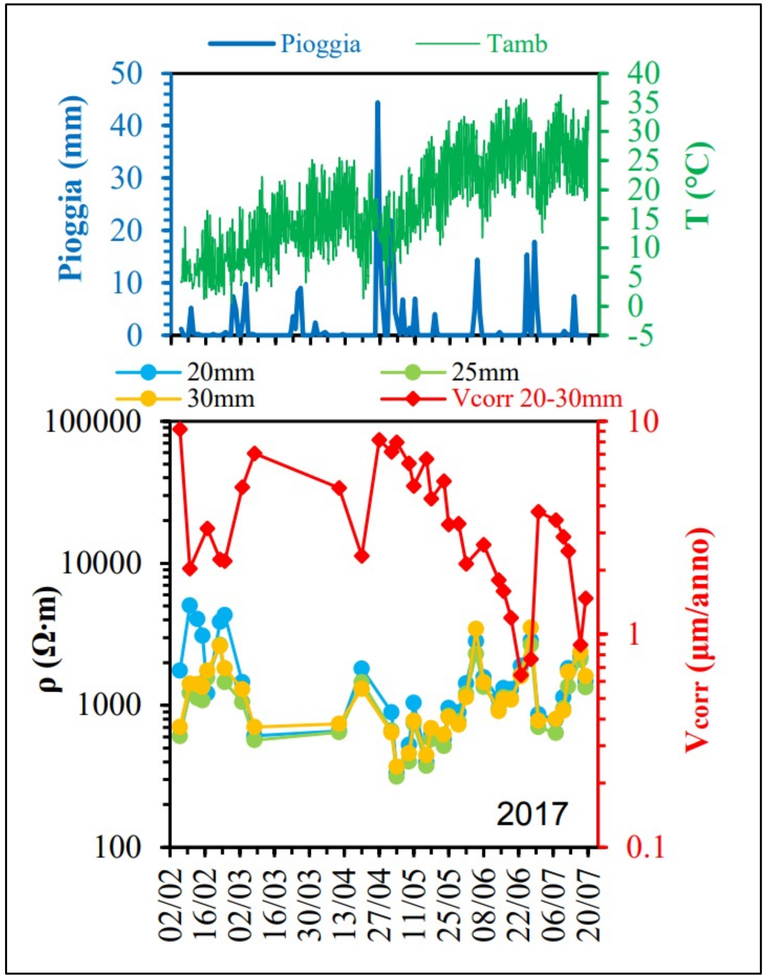
Preventative maintenance



Preventative maintenance



Monitoring



Source: M. Gastaldi , M. Messina, “Corrosion propagation in carbonated reinforced concrete structures,” 2021

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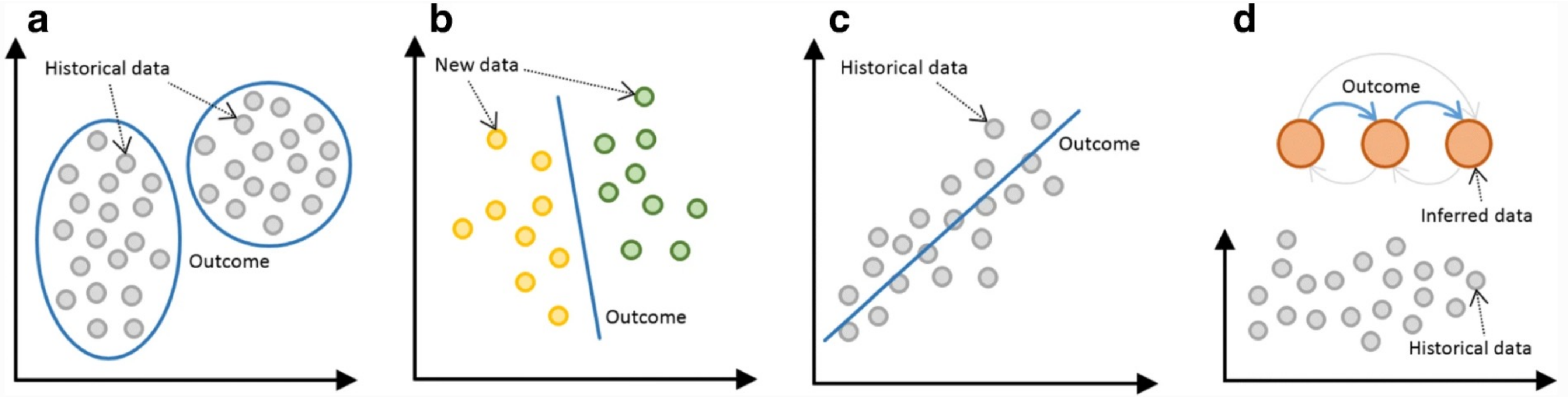
Machine learning



Problem categories that benefit from machine learning. **a** Clustering. **b** Classification. **c** Regression. **d** Rule extraction

https://jisajournal.springeropen.com/articles/10.1186/s13174-018-0087-2

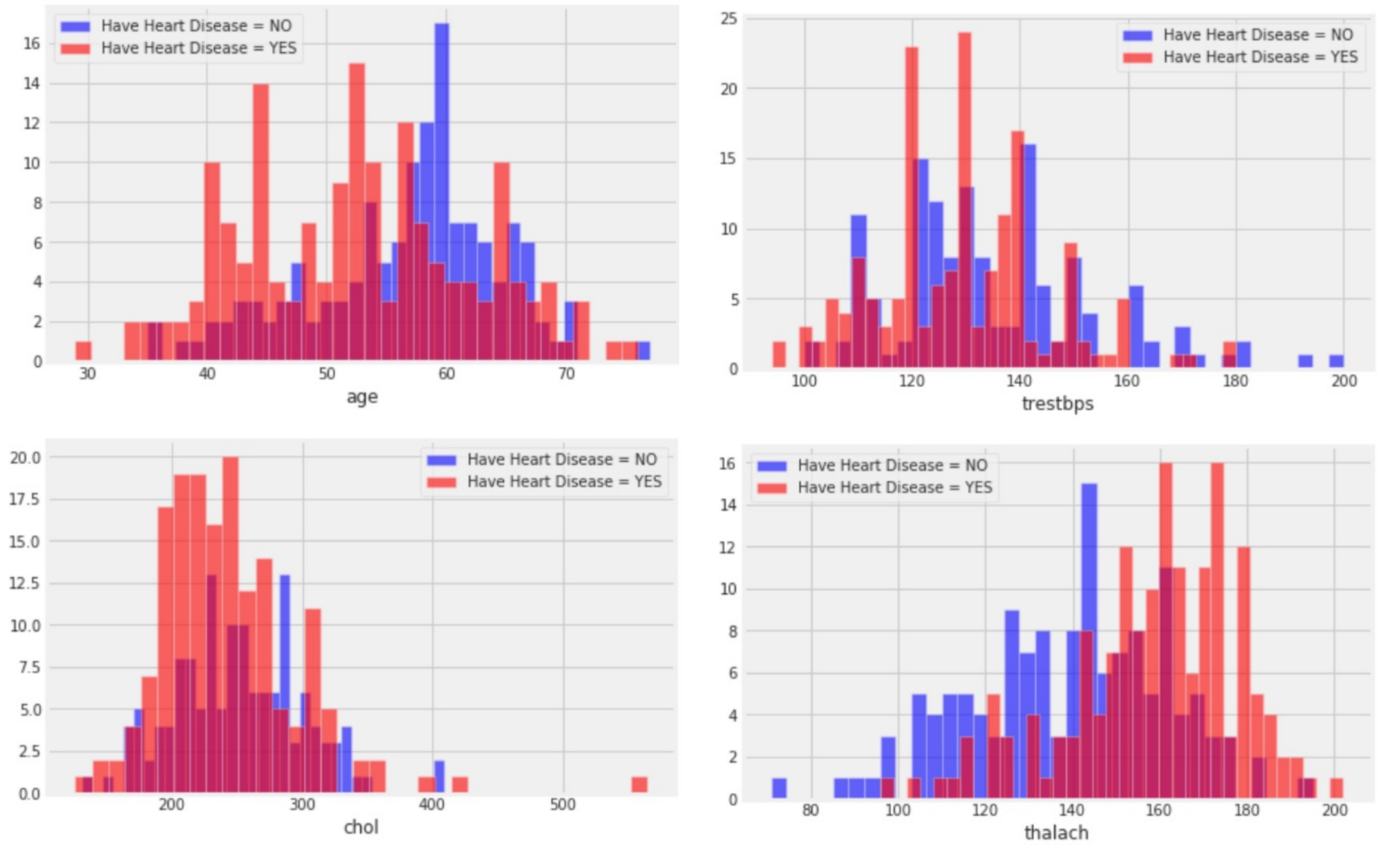
Proof of concept

Analogy

Independent variables:

- Age
- Chest pain type
- Resting blood pressure
- Serum cholesterol
- Max heart rate achieved
- Etc.

Can ML be used to predict if the patient has a heart condition or not?



https://thecleverprogrammer.com/2020/11/10/heart-disease-prediction-using-machine-learning/

Proof of concept

Analogy

Independent variables

Dependent variable

1	age	sex	cp	trestbps	chol	fbs	restecg	thalach	exang	oldpeak	slope	ca	thal	condition
2	69	1	0	160	234	1	2	131	0	0.1	1	1	0	0
3	69	0	0	140	239	0	0	151	0	1.8	0	2	0	0
4	66	0	0	150	226	0	0	114	0	2.6	2	0	0	0
5	65	1	0	138	282	1	2	174	0	1.4	1	1	0	1
6	64	1	0	110	211	0	2	144	1	1.8	1	0	0	0
7	64	1	0	170	227	0	2	155	0	0.6	1	0	2	0
8	63	1	0	145	233	1	2	150	0	2.3	2	0	1	0
9	61	1	0	134	234	0	0	145	0	2.6	1	2	0	1
10	60	0	0	150	240	0	0	171	0	0.9	0	0	0	0
11	59	1	0	178	270	0	2	145	0	4.2	2	0	2	0
12	59	1	0	170	288	0	2	159	0	0.2	1	0	2	1
13	59	1	0	160	273	0	2	125	0	0	0	0	0	1
14	59	1	0	134	204	0	0	162	0	0.8	0	2	0	1
15	58	0	0	150	283	1	2	162	0	1	0	0	0	0
16	56	1	0	120	193	0	2	162	0	1.9	1	0	2	0
17	52	1	0	118	186	0	2	190	0	0	1	0	1	0
18	52	1	0	152	298	1	0	178	0	1.2	1	0	2	0
19	51	1	0	125	213	0	2	125	1	1.4	0	1	0	0
20	45	1	0	110	264	0	0	132	0	1.2	1	0	2	1
21	42	1	0	148	244	0	2	178	0	0.8	0	2	0	0
22	40	1	0	140	199	0	0	178	1	1.4	0	0	2	0
23	38	1	0	120	231	0	0	182	1	3.8	1	0	2	1
24	34	1	0	118	182	0	2	174	0	0	0	0	0	0

Linear Regression RMS Error= 0.33 or 33%
determines goodness of fit for the model

Logistic Regression Confusion Matrix

True Positive	False Positive
140	18
False Negative	**True Negative**
27	109

Error=0.15 or 15%

Machine learning for service life evaluation

Dataset from inspection reports

	Year 1	Year 2	…	Year i	…	Year n
ID 1						
ID 2						
…						
ID i				{ }		
…						
ID n						

{
Type
Age
Condition 1
Condition 2
…
Amount of damage
Rating
Repair Y/N
}

Conclusions

- Focus on chloride-induced corrosion of steel reinforcement
- Review of service life modeling
- Overview of state-of-the-art methodology for diagnosis and prognosis of reinforced concrete structures
- Discussion on how innovation can add value to evaluating the residual life of existing structures

Questions?

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