PIANC APAC 2022 – 2nd PIANC Asia Pacific Conference – Melbourne , 4-7 September 2022

"Leaders and Professionals Coming Together"

Appropriate Test Data & Durability Design of Concrete Marine Structures

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1 BCRC WA, 2 BCRC Vic

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Owners Conundrums

- New Structures
  - How do I design for concrete durability given:
    - AS Codes only provide deemed to satisfy requirements that
      - Are not tailored to all environments
      - Do not include a measure of durability
      - May not give the reliability wanted
      - Do not include many products avaialble
- Existing Structures
  - How do I reliability account for, and plan maintenance for, a life when:
    - I don't know the current condition or rate of decay
    - Wether I am headed to catastrophic failure

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Infrastructure Value – Responsibility of Owners

- "Infrastructure value is 3x that of the capitalisation of all companies." Marcel Poser, Chairman, Proceq.
- " …AU$21.9 trillion gap between what is currently invested in infrastructure, and what is actually needed." Marie Lam-Frendo, CEO, Global Infrastructure Hub.
- "..in 10 to 15 years, Australia's bridges will be in the same condition as the United States, where 30 per cent of 625,000 bridges are listed as functionally obsolete or structurally deficient" Dr Colin Caprani, Monash University.

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Deemed to Satisfy - Splash (C2) Standard Compaction

Durability Requirements	Design Life: AS4997 25yrs Small Craft	AS4997 50yrs Normal Commercial	AS4997 100yrs Special Structures	AS3600 50yrs Concrete Structures	AS5100 100yrs Concrete Bridges
Strength (MPa)	50	Why the difference when DtS and exposure similar?		50	55
Min. Cover (mm)	65			65	80
Curing	7d water			7d water	14d water
Cement Type	GP & GB	-	-	-	FA/Slag/SF
Min. Cement (kg/m^3)	400	-	-	-	470
Max. w/c	0.40	-	-	-	0.36
Durability Indicator	-	-	-	-	VPV etc

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New Design Approach

AS 4997 25yrs

What about:

- 50 or 100 years?
- Lowest Life Cycle Costs?
- Prestressing Protection?
- Using Alternative Steels?
- Using Better Concrete

- Could be inadequate or overkill
- Cement systems critical
- Curing major impact

New Approach ISO 16204; fib Bulletin 34

- Design Requirements
  - Defined Limit State
  - Reliability, Design Life and Exposure
- Concrete Design Variables
  - Cover
  - Chloride diffusivity
    - Initial and Aging factor
  - Base Chloride
  - Surface Chloride
- Testing to confirm assumptions

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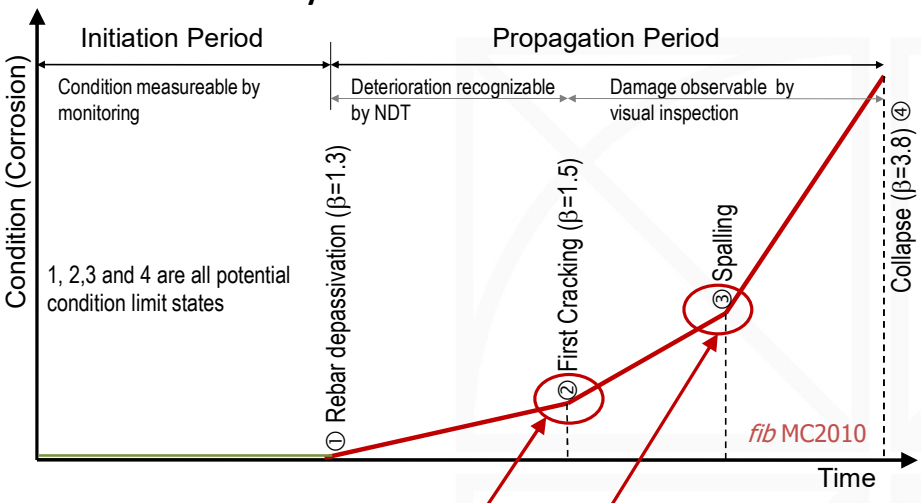
Define Limit States

- **Condition Serviceability Limit States**



- **Performance Limit States**
- **Operational Limit States**

e.g. Australia

e.g. Indonesia

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Design Life – AS 1170 Reliability vs Consequence

Serviceability Limit State (After earthquake, snow or wind event)	Design Life (yrs)	Importance Level	Prob. of Failure
1 No repair required		1	-
	0.5-100	2-4	4%
		5	Case by Case
2 Maintains operational continuity	0.5-50	1-3	4%
	5-25	4	0.4%
	50		0.2%
	100		Hazard Anal.
	5-100	5	Case by Case

Typical SLS PoF 4%

Increasing reliability with importance

Used for snow, wind and earthquake.
Durability not specifically included

Importance	Description
1	Minor structures. Failure not likely to endanger human life
2	Normal structures.
3	Major structures (affecting crowds)
4	Post disaster function or dangerous activities
5	Exceptional structures

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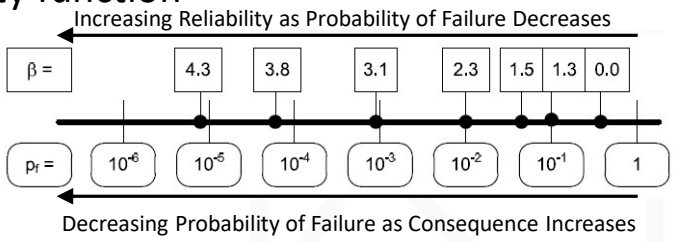
Target Reliabilities – ISO 2394

- Inverse probability function

Target Reliabilities & Failure Probability



- ISO 2394

Relative costs of safety measures	Consequence of failure: *Small*	*Some*	*Moderate*	*Great*
High	0	1.5	2.3	3.1
Moderate	1.3	2.3	3.1	3.8
Low	2.3	3.1	3.8	4.3

e.g. deck soffit

SLS

e.g. crane beams

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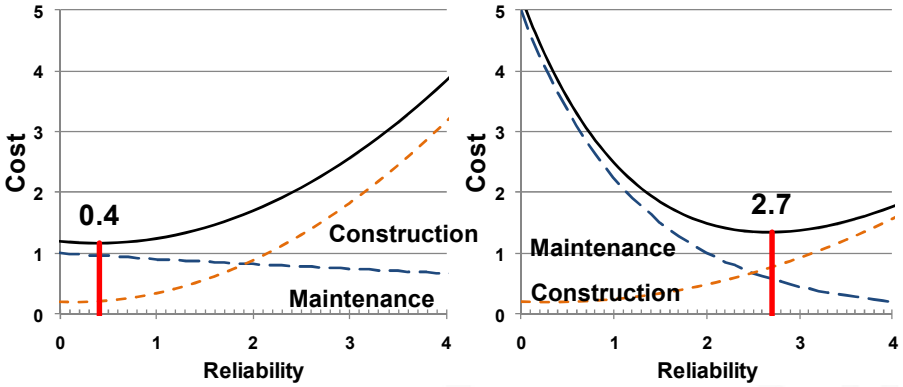
Required Relaibility



Low reduction in maintenance cost with increasing reliability
High increase in construction cost to increase reliability
= Low design reliability

High reduction in maintenance cost with increasing reliability
High increase in construction cost to increase reliability
= High design reliability

Balanced Reliability Approach

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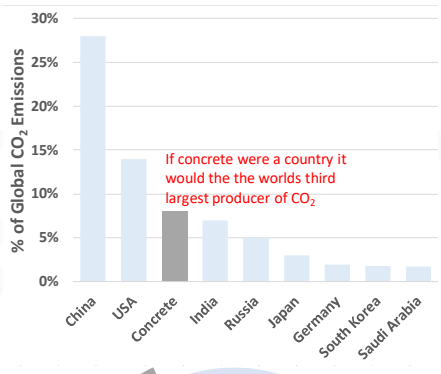
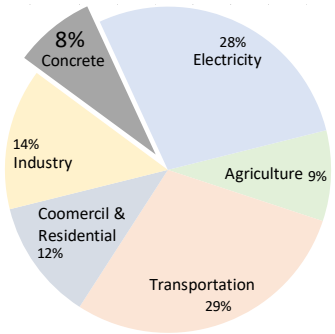
Design Life

- Financial – Net present value of replacement
  - House 50 yr design life
  - Bridge 100 yr design life
  - Water tank 50→100yr design life
  - Marine Structures
- Sustainability
  - Fib Model Code 2020
    - Based on Sustainable design
    - Include design of existing structures





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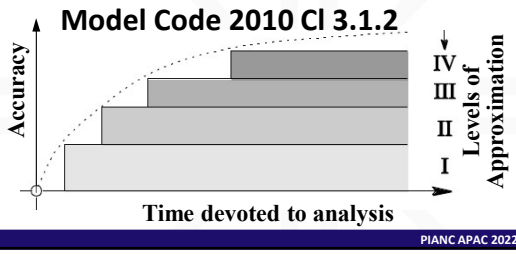
Levels of Approximation (LoA)

- All analysis are approximations of reality
- Different levels of approximation have different accuracy
- Refine solutions by better parameters estimation



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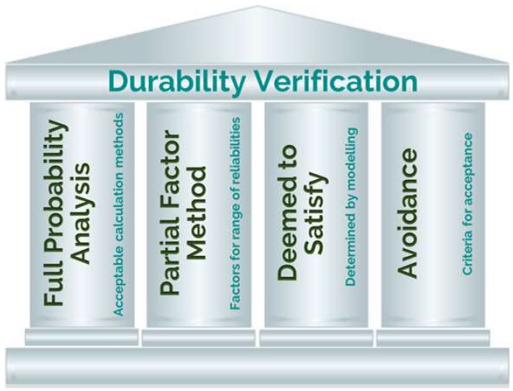
Verification Methods

Increasingly Conservative

- Full probability analysis
  - Calculates the probability of failure at the end of the design life
- Partial factor analysis
  - Determined by researchers for key variables for practitioners to use deterministically in the equations.
- Deemed to satisfy
  - Currently determined by experience but likely to be set by FPA.
- Avoidance
  - the use of something that eliminates the failure risk.

$$C_{crit}=C_0+(C_{s,\Delta x}-C_0)\times\left[1-\mathrm{erf}\left[(a-\Delta x)/(2\times\{D_{app,c}\times t\}^{0.5}\right]\right]$$



Deterministic modelling is not included

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Typical Chloride Model Inputs (fib Bulletin 76)

$$C(x,t) = C_0 + (C_{S,\Delta x} - C_0) \cdot \left[1 - erf \frac{x - \Delta x}{2 \cdot \sqrt{D_{app}(t) \cdot t}}\right] \qquad D_{app,B}(t) = k_e \cdot D_{RCM}(t_0) \cdot \left(\frac{t_0}{t}\right)^{\alpha_B}$$

Unit	Name	Mean	Std. Dev.	Beta a	Beta b	Units	Source
D_{RCM0}	**Migration coef.**	**5.48**	**0.07**			**10^{-12} m²/s**	**Measured**
c	**Cover**	**55**	**5**			**mm**	**Design assumption**
C_{crit}	**Critical chloride**	**0.6**	**0.15**	**0.2**	**2**	**Wt % cem.**	**Bulletin 76 black, atmos**
$C_{s\Delta x}$	**Surface chloride**	**2**	**0.2**			**wt.%/c**	**Bulletin 76 Atmospheric**
α	**Age factor**	**0.65**	**0.12**	**0**	**1**	**constant**	**Bulletin 76 Atmospheric**
t_0	Test age	0.255				year	Test certificate
t	Design life	100				years	Specification
b_e	Temperature coef.	4800	700			constant	Bulletin 76
T_{ref}	Ref. Temp.	296				degrees K	23C
T_{real}	Actual Temp.	301	8			degrees K	28C
Δx	Surface zone	0				mm	General for atmospheric
c_0	Base chloride level	0.05				wt.%/c	Assumed
n	No of simulation	100000				constant	Scilab setting

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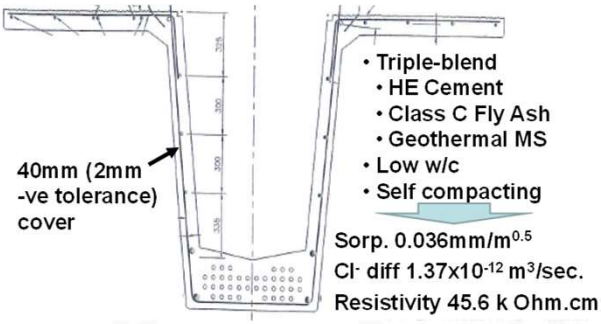
Modelling/HPC – Lower Cost, Higher Sustainability

- Lighter beams
- Longer spans
- Fewer piers
- Smaller cranes
- Less concrete
- Less prestress
- 'Cost advantage 20% of the bid price, i.e. some $20 million'



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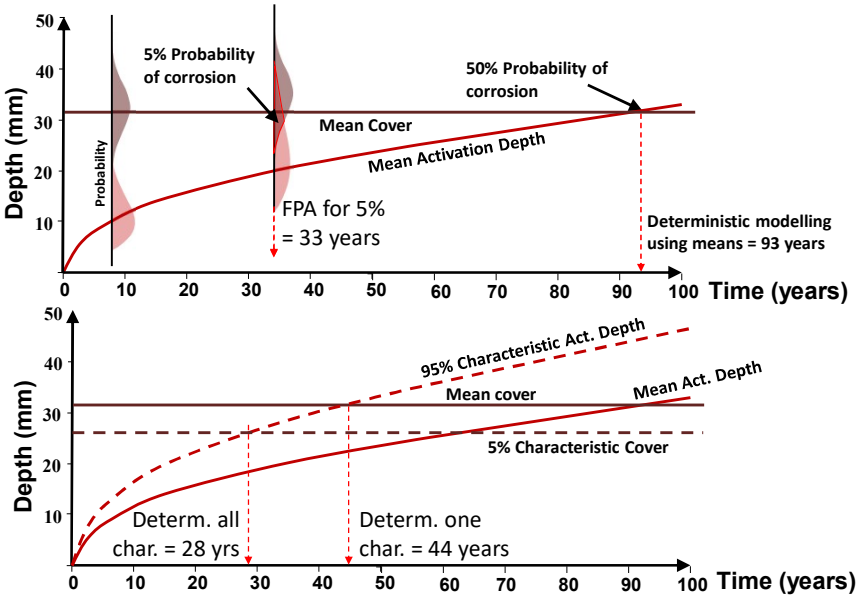
L.McSaveney et al. *"SCC for Superior Marine Durability - New Zealand's new Tauranga Harbour Link"* 2011

Understanding Variables as Distributions



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Tests for Chloride Ingress Rate - New Structures

- Very basic structure
  - Use appropriate deemed to satisfy
- Higher investments
  - Initial design
    - Check DtS using assumed values in initial design
    - Consider alternative design against DtS calculation
  - Pre Construction
    - Test chloride diffusivity of cylinders
    - Test chloride diffusion of mock up
  - During Construction
    - Test chloride diffusivity of as built
    - Assess aging factor by repeat tests
    - QA tests - Resistivity

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Surface Chloride Levels

AS3600		EN201		Bulletin 76	CIA Z7/02		
Cl	Loc.	Cl	Loc.	Mean S_{Cm} COV =0.45	Cl	Loc.	S_{Cu}
A2	Beyond 50Km	-	-	-	XS1a	Calm: 1-5km Surf: 5-50+km	μ=0.5
B1	Near coastal 1-50km	XS1	Coastal	1%	XS1b	Calm: 50m-1km Surf: 1-5km	μ=1.0
B2	Coastal 0-1km			2%	XS1c	Calm: 0-50m Surf: 400m-1km	μ=2.0
C1	Marine	XS3	Marine	2-4%	XS1d	Calm:N/A Surf 0-400m Marine	μ=3.0

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Aging Factor (fib Bulletin 76)

High Aging Factor gives long design life

Cement Type w/c 0.4-0.6	Aging Factor BetaD (μ/σ) a=0.0, b=1.0 **Submerged, Tidal, Splash Spray Zones**
CEM 1 (GP Cement)	0.30/0.12
CEMII/A-D (6-10% Silica fume)	0.40/0.16
CEMII/B-V (21-35% Fly Ash)	0.60/0.15
CEMIII/A (36-65% S)	0.40/0.18
CEMIII/B (66-80% S)	0.45/0.20
CEM1 +5% SF	0.40/0.16
	Atmospheric
All	0.65/0.12

Same w/c & strength; Very different performance

Aging factor most influential factor on chloride ingress

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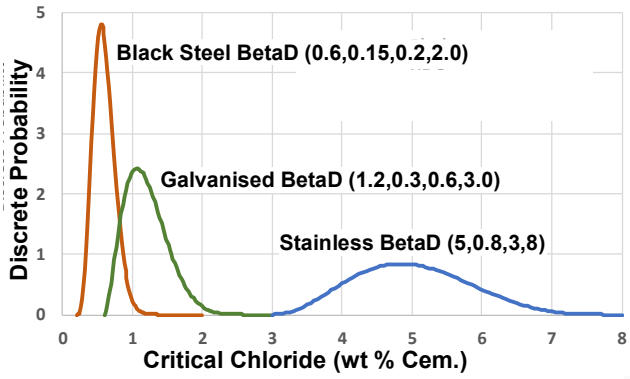
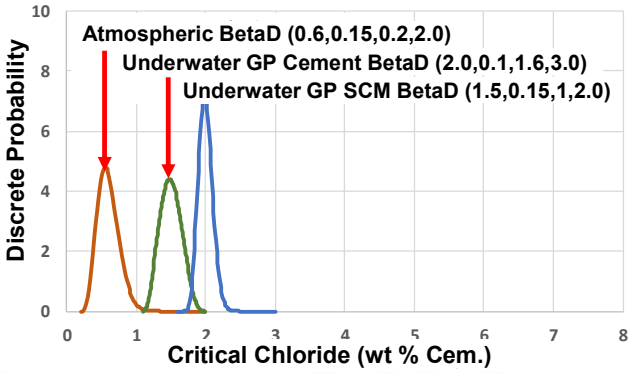
Critical Chloride Content





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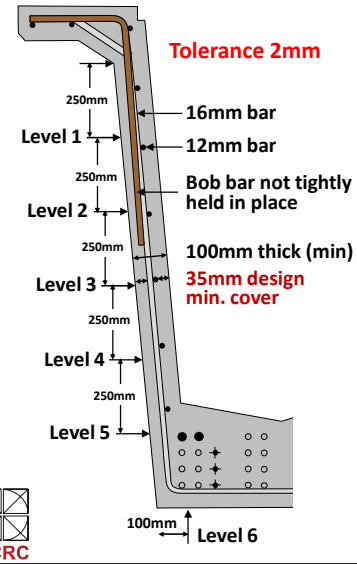
Low Cover on Coastal Structure

Section Through T-Roff



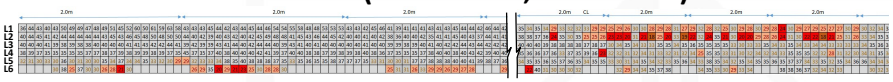
Category Difference

1 Affected by bob bars sticking out

2 1st attempt to correct bar using 2 12mm bars

Loc	Tests	Mean	Std. Dev.	95% Char.
Category 1				
L1	1552	42	8.8	27
L2	1552	38	9.2	**23**
L5	805	34	3.7	28
L6	521	32	5.2	**23**
Category 2				
L1	1628	38	7.8	25
L2	1625	39	6.8	**28**
L5	1269	42	6.6	31
L6	675	34	3.0	**29**
Cat. 1 & 2	15462	38.8	7.3	25.7
≥25mm	15188	39.1	6.9	26.9

Plot of Cover on One Face (0-5mm low; >5mm low)



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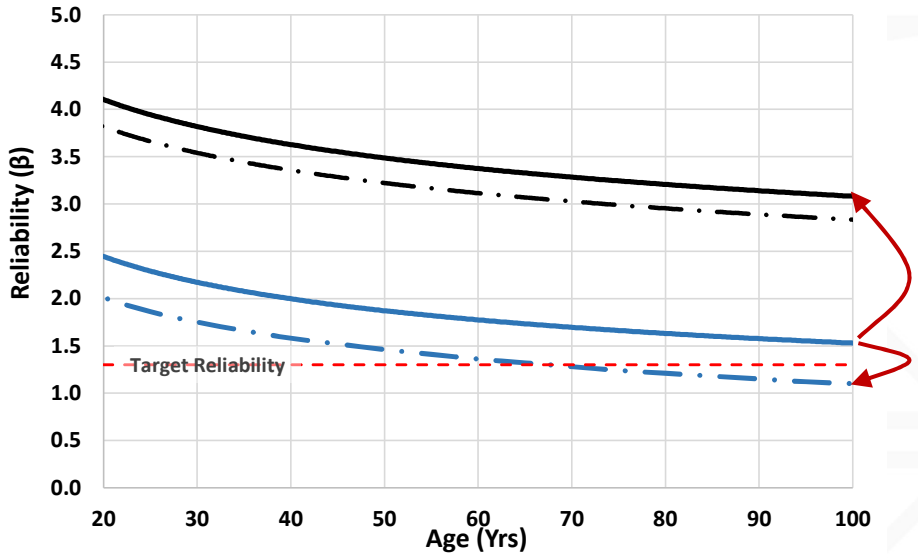
CREAD - Modelling

$$C(x,t) = C_0 + (C_{S,\Delta x} - C_0) \cdot \left[1 - erf \frac{x - \Delta x}{2 \cdot \sqrt{D_{...}(t) \cdot t}}\right]$$



HDG Improves reliability and allows reduced cover

Reduced cover not acceptable

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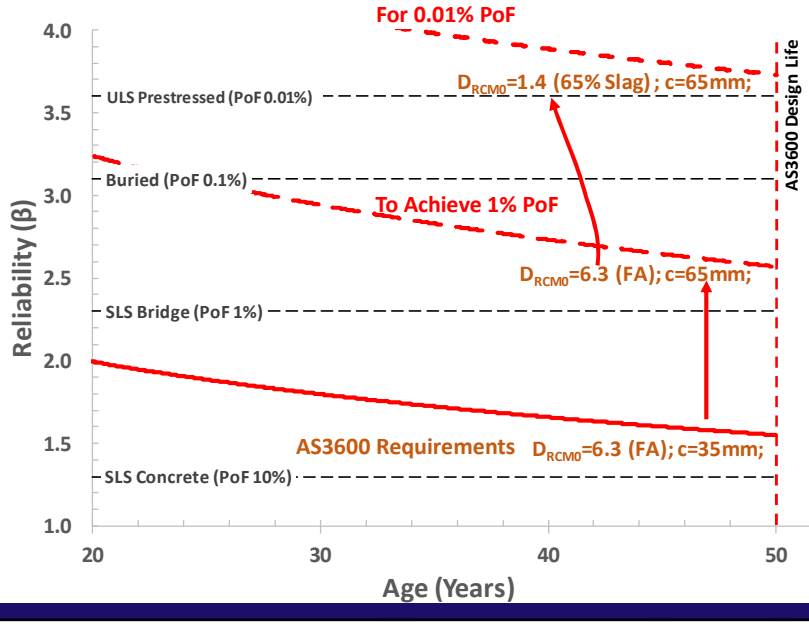
B2/XS1c Exp; 50MPa; Tol -5,+10; SCM; S_c=1.15%



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Ponte Morandi

In 2018 the 1967 Morandi Bridge (Genoa) collapsed due to corrosion of a stays cable. 43 died. The replacement bridge has robots for cleaning and inspection.

1. Durability design not based on protecting against catastrophic failure, i.e., reliability was inadequately considered. How to provide high reliability?
2. 'Lack of redundancy' – How to achieve required redundancy?

Livio's "Brilliant Blunders" - Ignoring Low Probability Outcomes. 'Certainty is generally an illusion'. Do not just accept the most likely answer. Lord Kelvin theory on earths age based on cooling rate did not account for earths liquid core.

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Conclusions

Why not?

- Possibly lower costs by:
  - use of improved materials
  - tailored design
- Better definition of owner needs and wants
- Better understanding of expected performance
  - Reduced risk

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