Asset Level Modelling of RISKs In the Face of Climate Induced Extreme Events and ADAPTation (RISKADAPT)

Material degradation under climate change

Workshop on “Risk assessment of structures under Climate Change ”

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RISKADAPT
Modeling of Risks and Adaptation

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Outline

- Available material degradation models by standards and literature for concrete and steel
- Application process of the material degradation models on RISKADAPT pilots
- Results of the application
- Conclusions

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Material degradation of structural steel

- According to ISO 9223 & 9224 (2012), major factors that affect the corrosion rate of steel are:
  - Temperature (T)
  - Relative Humidity (RH)
  - SO_2 concentration
  - Cl^- concentration

Thickness loss of steel sections

- **Thickness loss** as a function of time is considered to follow a **power-law during the first years** of exposure:

$$x(t) = At^B$$

Where: $x(t)$: is the total loss of thickness (in μm), t: is years of exposure, A: represents the corrosion losses for the first year in μm, B: is a coefficient that characterises the protective properties of corrosion products

- Because of the formation of corrosion products on the metal surface, the initial corrosion rate usually decreases over a long−term period, so the initial power−law is followed by a linear law.

- The **total thickness loss** is estimated by:

$$x(t) = A{t_{st}}^B + C(t - t_{st})$$

Where: $x(t)$: is the total loss of thickness (in μm), t_{st}: is the year when stabilization begins, t_{st}=20 as per ISO 9224 (2012), C: is the yearly gain in corrosion losses of metals during the stationary stage in μm/year, which is equal to the corrosion rate at t_{st}.

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Impact of Climate Change on steel corrosion

- ISO 9223 (2012) proposes the following equation for the **1st year corrosion rate** of **carbon steel**:

$$r_{corr} = 1.77Pd^{0.52}e^{0.020RH+f_{st}} + 0.102Sd^{0.62}e^{0.033RH+0.040T}$$

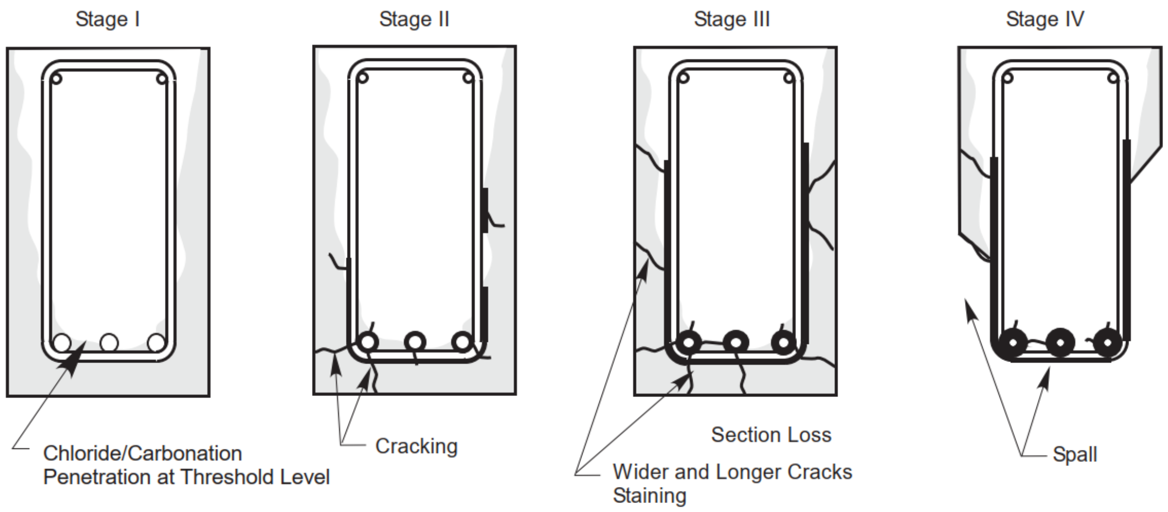
where: $f_{st} = 0.15(T-10)$ if $T \leq 10°C$ and $f_{st} = -0.054(T-10)$ otherwise, r_{corr}: is first year corrosion rate of steel (μm/year), T: is the annual average temperature (in °C), RH: is the annual average relative humidity (%), Pd: is the annual average Sulphur Dioxide (SO_2) deposition in $mg/m^2\,day$, Sd: is the annual average chlorides (Cl^-) deposition in $mg/m^2\,day$

- The 1st year corrosion rate can be used as the factor A in the total corrosion losses equation ($A = r_{corr}$)

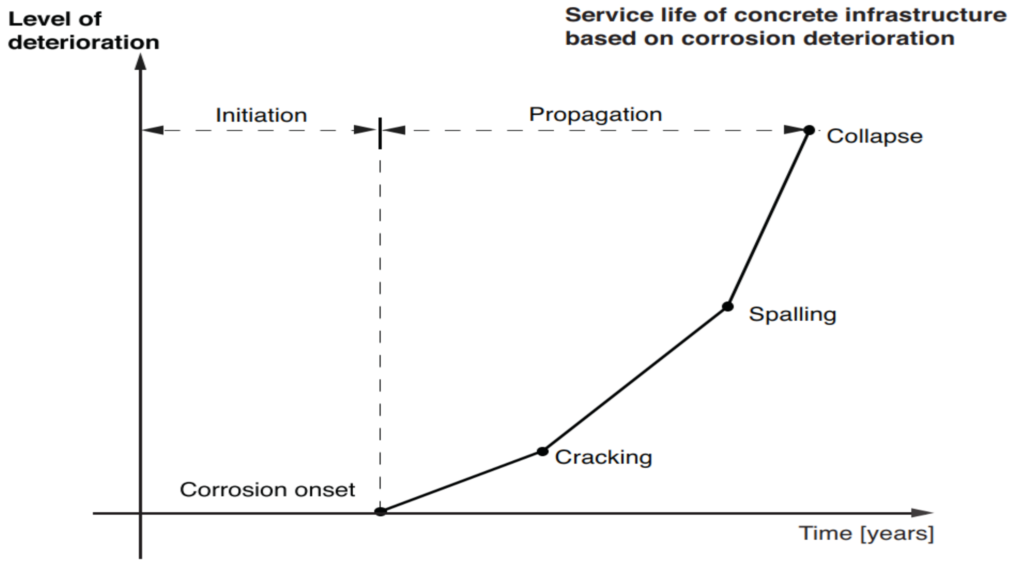
Effect of climate parameters

- Temperature: an increase in temperature lead to increase in the corrosion rate
- RH: For a constant temperature, an increase in RH will lead to increase in the corrosion rate
- SO_2 : An increase in SO_2 will cause increase in the initial rate of corrosion – recent legislation has resulted in decreasing SO_2 concentrations
- Cl^- : Cl^- with SO_2 has a synergistic effect on the rate of corrosion – the chloride deposition is not expected to change dramatically in the future (Sousa et al., 2020)

Material degradation of reinforced concrete



Source: Higgins et al. (2003)



Source: fib (2000)

- **Environmental parameters** that affect the deterioration of concrete members:
  - Temperature (T)
  - Relative Humidity (RH)
  - CO_2 concentration – carbonation-induced corrosion
  - Cl^- concentration – chloride-induced corrosion

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Carbonation-induced corrosion

Corrosion Initiation – Time to corrosion initiation

- The carbonation depth (X_C in cm) can be estimated as a function of time (Steward et al., 2012):

$$X_C(t) = \left[(2/a)D_{CO_2}(t)C_{CO_2}(t)(t - t_0)k f_T(t) f_{RH}(t)\right]^{1/2}[t_0/t]^n$$

- The variables included in the model take into account the synthesis of concrete (e.g., amount of cement, ration of CaO, etc.) and the environmental conditions at the structure's site (e.g., temperature, RH, etc.)
- If the original cover depth is known, then the time to initiation can be estimated, if X_C is set equal to cover depth

Corrosion Propagation – Rate of corrosion

- Assuming a uniform and constant corrosion rate during the propagation period, the progressive loss of rebar diameter in μm (attack penetration) can be expressed as (Markeset & Mydral, 2008):

$$P(t) = 0.0116\, i_{corr}\, t$$

- The corrosion rate is a function of several parameters, including temperature, humidity (affecting resistivity), and age of concrete (affecting the degree of hydration).

Chloride-induced corrosion

Corrosion Initiation – Time to corrosion initiation

- The chloride penetration depth (X in m) can be estimated as an empirical model suggested by DuraCrete project:

$$X(t) = 2K(Dt)^{0.5}$$

- The variables included in the model take into account the exposure time, chloride concentration as percent by weight of cement, and the chloride diffusion coefficient
- If the original cover depth is known, then the time to initiation can be estimated, if X is set equal to cover depth

Corrosion Propagation – Rate of corrosion

- Corrosion rate of diameter decrease in steel rebars can be estimated by the following model (Rodriguez and Andrade, 1990):

$$\Phi(t) = \Phi(i) - 0.023294\, a\, i_{corr}\, t$$

- Where: i_{corr} chloride-induced corrosion rate that is affected by temperature

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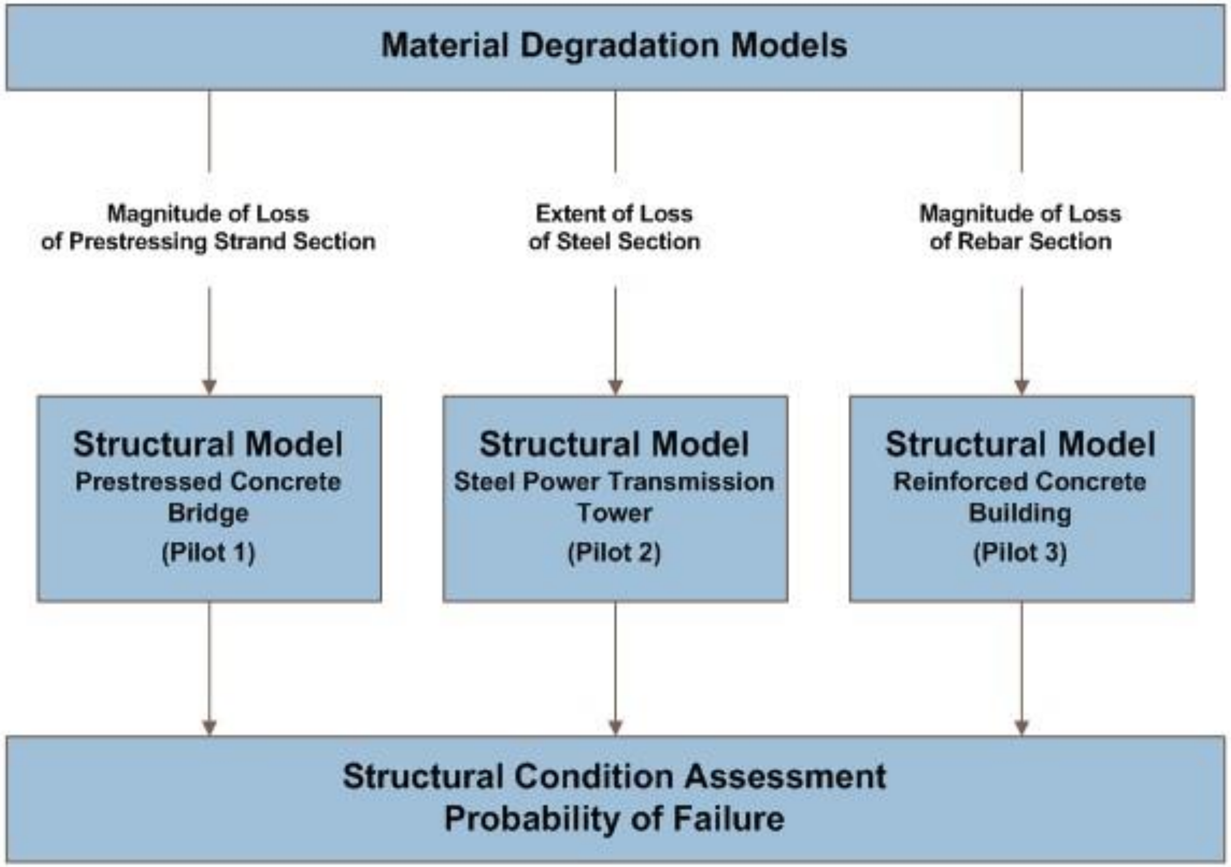
Material degradation models application in RISKADAPT



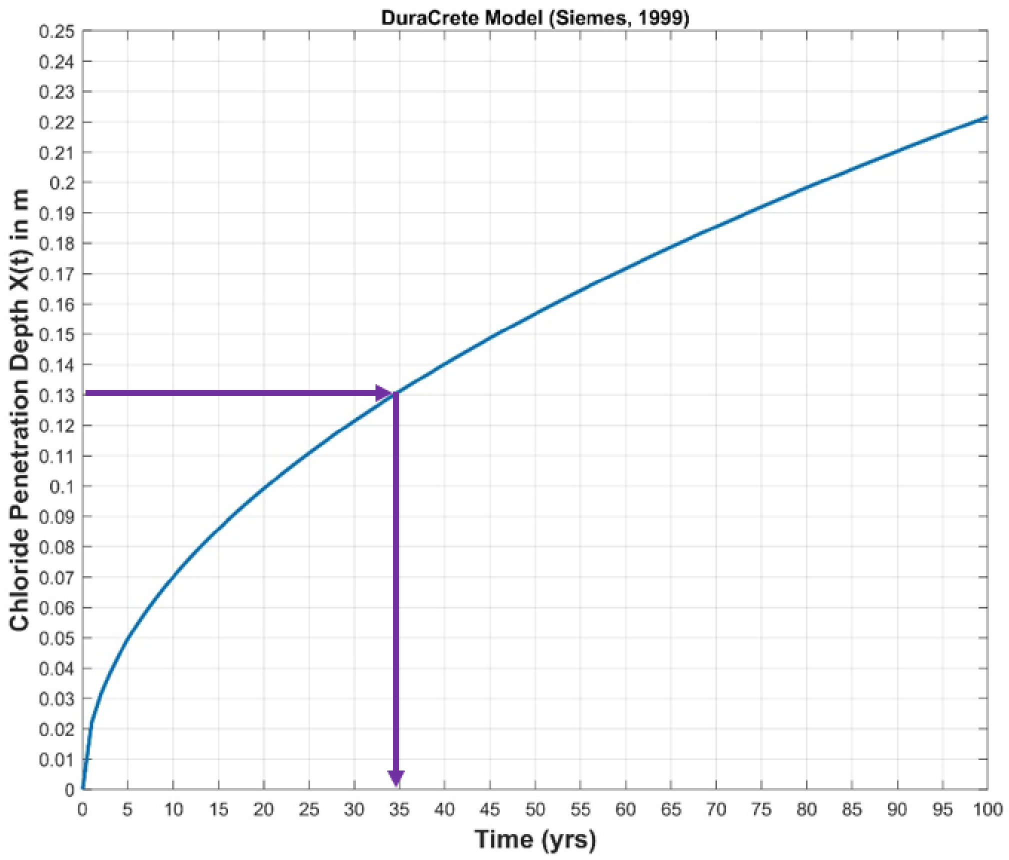
Pilot 1: Polyfytos bridge - Kozani, Greece

Assumptions:

- The bridge was built in 1975 – Exposure time: t = 49 yrs
- Average temperature: T = 22 °C
- Cover depth of prestressing strands = 13 cm
- Main cause of corrosion: de-icing salts => **chloride-induced corrosion**

Current status (t = 49 yrs)

- Following the chloride penetration figure the cover depth was exhausted 35 years after construction.
- Corrosion initiation started around 2010 (14 yrs ago)
- Resulting **loss of diameter** due to corrosion as of today = **12.74 mm**



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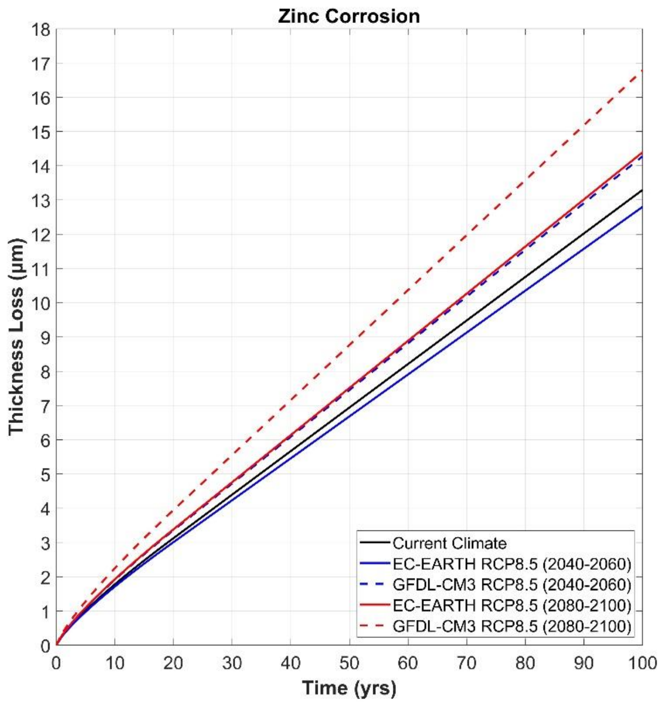
Pilot 2: Steel Transmission Towers – East Finland

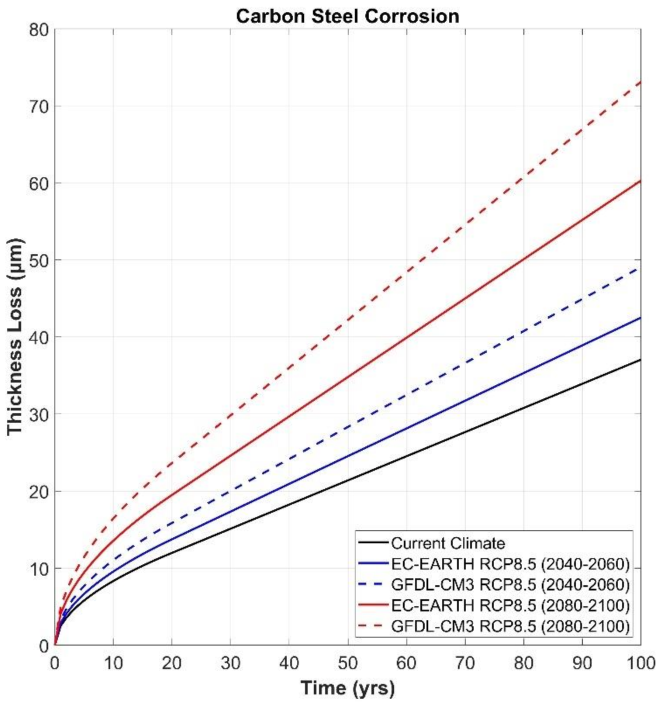
Assumptions:

- The line was built in 2020 – Exposure time: t = 4 yrs
- Zinc protection layer thickness not known – It is assumed as 70 µm for thickness 3-6 mm and 85 µm for thickness > 6 mm as per ISO 1461:2009
- The effect of environmental pollutants (SO_2 & Cl^-) was neglected, since data from the area show very low concentrations of both pollutants
- Five different climate models considered:

Climate	Model	Average Temperature (^oC)	Relative Humidity (%)
Current	ERA5	3.04	80.36
Future (2040-2060)	EC-EARTH-RCP 8.5	4.62	77.96
Future (2040-2060)	GFDL-CM3-RCP 8.5	5.44	79.69
Future (2080-2100)	EC-EARTH-RCP 8.5	7.35	78.02
Future (2080-2100)	GFDL-CM3-RCP 8.5	8.38	80.60

Pilot 2: Estimated loss of zinc and carbon steel on tower sections





Results:

- Even with the worst climate scenario the zinc loss will be less than 18 μm after 100 yrs – The zinc protection layer will not be exhausted
- Ignoring the zinc protection layer, the estimated carbon steel loss after 100 yrs will be less than 80 μm = 0.08 mm => negligible

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Pilot 3: Cattinara Hospital – Trieste, Italy

Assumptions:

- The hospital was built in 1974 – Exposure time: t = 50 yrs
- The hospital is in urban environment
- Cover depth of reinforcing rebars: 4 cm
- Average Temperature: T = 15.5 °C
- Average Relative Humidity: RH = 65%
- Main cause of corrosion: **carbonation-induced corrosion**

Current status (t = 50 yrs)

- By applying the models of carbonation-induced corrosion the estimated loss after 50 yrs of service (i.e., today) is around **0.41 cm** – far less than 4 cm => **carbonation depth has not reached steel bars yet.**

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Pilot 3: Cattinara Hospital – Trieste, Italy

Future status

- Most severe scenario with 750 ppm CO_2 was assumed
- Increase in temperature by 3.5 °C
- In 50 yrs from today (2074): carbonation depth = 0.64 cm
- Total carbonation depth since construction (1974): 0.41 + 0.64 = 1.65 cm < 4 cm
- **Climate change is not expected to affect Cattinara hospital in terms of corrosion**

Conclusions

- For Pilot 1 (bridge in Greece) corrosion of prestressed tendons must have started since more than a decade (appr. 14 yrs)
- A significant reduction thickness of more than 12 mm has been estimated for the prestressing strands of pilot 1
- Pilot 2 (transmission towers in Finland) has not been affected from steel corrosion and is not going to be significantly affected in the future
- Pilot 3 (hospital in Italy) has not been affected so far, while climate change is not expected to affect the Cattinara hospital for the next 50 years.

THANK YOU!

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