Time-Dependent Degradation of Bridge and Tunnel Materials

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Objectives

To develop time-dependent material degradation models for concrete and steel bridges or tunnels exposed to ageing and Climate Change (CC) that will:

- ✓ Provide structural analyses with time-dependent, quantitative input on loss of steel thickness due to corrosion
- ✓ Assess the impact of CC on material degradation
- ✓ Provide a map of estimated defects that will be used in subsequent Remoted Pilot Aircraft System (RPAS) measurements to assess the evolution of these defects

RPAS Input to the Modules on Material Deterioration

- ✓Location, width and depth of cracks in steel and concrete members
- ✓Location and size of spalled areas in concrete members
- ✓Location of exposed steel bars in concrete members
- ✓Location and size of corroded areas in steel members

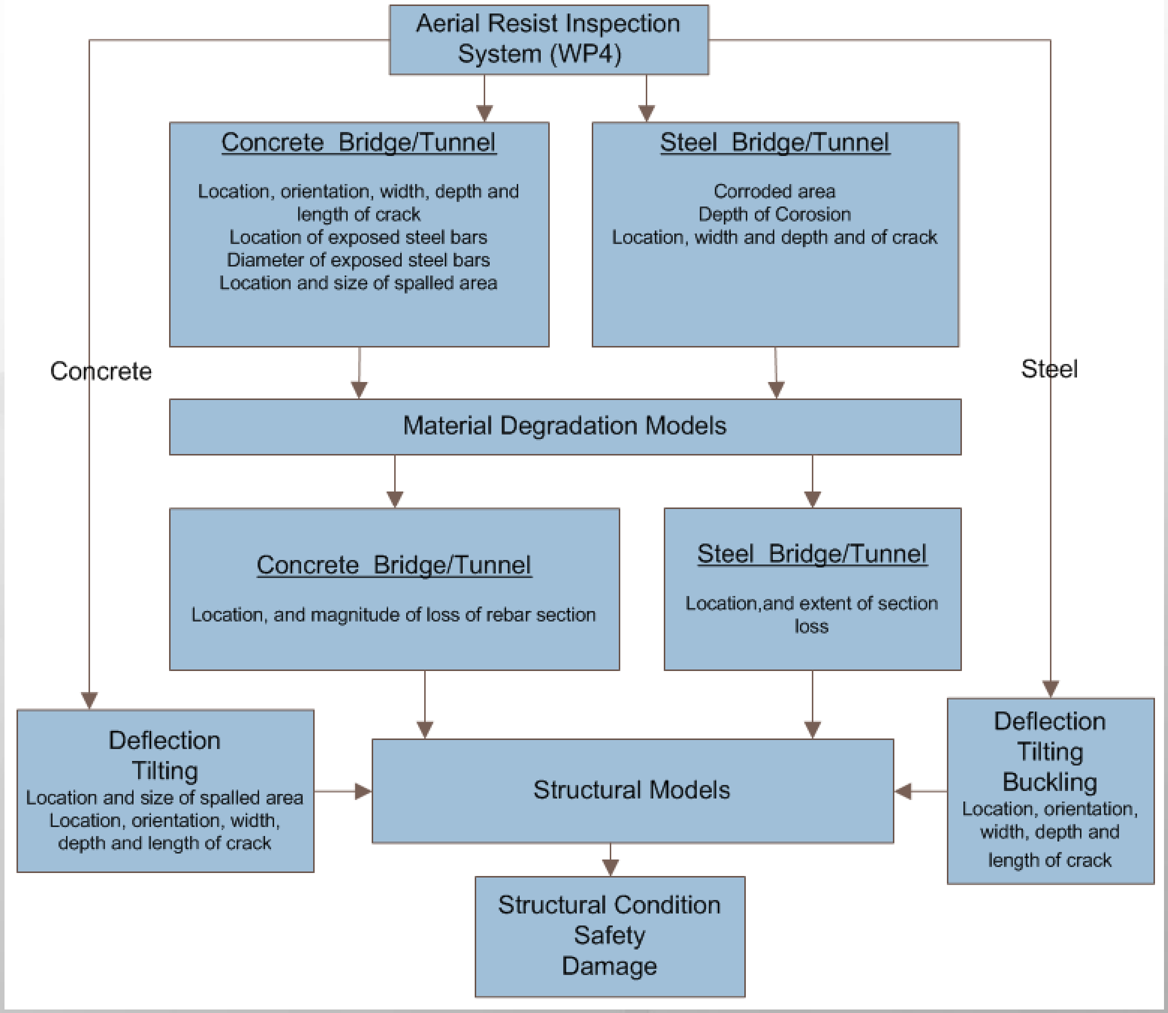
Output of Material Deterioration Modules

The Modules on Material Deterioration will provide the structural assessment with:

✓ Location and magnitude of rebar section loss in concrete members

✓ Location and magnitude of metal section loss in steel members

Flow Diagram



Corrosion Degradation of Structural Steel

Estimation is exclusively based on RPAS measurements of corrosion depth:

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

where:

$\boldsymbol{x}$: is the depth of corrosion (in μm)

$\boldsymbol{t}$: is the time of exposure (in yrs)

$\boldsymbol{t_{st}}$: stands for corrosion losses during the initial period of rapid corrosion

$\boldsymbol{A}$ and $\boldsymbol{B}$: are experimentally derived constants available in the literature that depend on the environment

$\boldsymbol{C}$: is an experimentally derived constant available in the literature that is the yearly gain in corrosion losses during the stationary stage after the initial stage of rapid corrosion (in μm/yr)

The above equation can be used in conjunction with future RPAS measurements of $\boldsymbol{x}$ in order to adjust the values of $\boldsymbol{A}$, $\boldsymbol{B}$ and $\boldsymbol{C}$ to the location of interest.

Impact of CC on the Corrosion of Structural Steel

Model 1: Effect of SO_2 in Combination with Temperature and Relative Humidity

Long-term corrosion losses (Panchenko & Marshakov, 2017):

$$\boldsymbol{x}(\boldsymbol{t}) = \left[\mathbf{3.54}(\boldsymbol{SO_2})^{\mathbf{0.13}} \times \boldsymbol{exp}\left(\mathbf{0.020}\boldsymbol{RH} + \boldsymbol{f}(\boldsymbol{T})\right) \times \boldsymbol{t}^{\mathbf{0.33}}\right] \times \mathbf{7.8} \quad (1)$$

where:

- $\boldsymbol{x}$: is the total loss of thickness (in μm)
- $\boldsymbol{t}$: is the time of exposure (in yrs)
- $(\boldsymbol{SO_2})$: is the concentration of SO_2 (in $\mu g/m^3$)
- $\boldsymbol{RH}$: is the relative humidity of air (%)
- $\boldsymbol{T}$: is the temperature (in ℃)
- $\boldsymbol{f}(\boldsymbol{T}) = \mathbf{0.059}(\boldsymbol{T} - \mathbf{10})$ when $\boldsymbol{T} \le \mathbf{10}$ ℃ , otherwise $\boldsymbol{f}(\boldsymbol{T}) = -\mathbf{0.036}(\boldsymbol{T} - \mathbf{10})$

The value of the square bracket is multiplied by 7.8 (specific density of steel) in order to convert the total mass loss (in g/m^2) of the original equation to the total loss of thickness (in μm).

Corrosion of Carbon Steel after One Year of Exposure (Model 1)

Corrosion after 1 year of exposure (μm)	SO_2 (μg/m^3)	RH (%)	T (℃)	Difference in corrosion rate after 1 year of exposure due to increased temperature (μm)	Drop in corrosion rate due to increased temperature (%)
26.957	1	60	11	1.873	6.95
25.084	1	60	13		
27.038	1	75	11	1.879	6.95
25.159	1	75	13		
29.500	2	60	11	2.050	6.95
27.450	2	60	13		
29.588	2	75	11	2.056	6.95
27.532	2	75	13		

Notes:

- ✓ Negative temperature effect in the interval 10℃ $\leq T \leq$ 21℃
- ✓ RH affects corrosion
- ✓ The level of SO_2 significantly affects corrosion. (However, in Europe, the annual mean SO_2 concentrations have decreased from 30 μg/m^3 to 2 μg/m^3 between 1988 and 2008)

Impact of CC on the Corrosion of Structural Steel

Model 2: Effect of Chloride in Combination with Temperature and Relative Humidity

Corrosion losses (Tidblad, 2012):

$$\boldsymbol{x(1) = 1.58(SO_2)^{0.52} \times e^{0.02RH+f_s(T)} + 0,102DCl^{0.62} \times e^{0.033RH+0.04T}} \quad (2)$$

where:

$\boldsymbol{x(1)}$: is the corrosion loss during first year (in μm)

$(\boldsymbol{SO_2})$: is the concentration of SO_2 (in $\mu g/m^3$)

$\boldsymbol{RH}$: is the relative humidity of air (%)

$\boldsymbol{DCl}$: is the chloride deposition (in $mg/m^2 day$)

$\boldsymbol{T}$: is the temperature (in ℃)

$\boldsymbol{f_S(T) = 0.038(T-10)}$ when $\boldsymbol{T \leq 10}$ ℃ , otherwise $\boldsymbol{f_S(T) = -0.054(T-10)}$

Notes:

- ✓ Chloride refers to salinity from sea water and does not include other possible sources.
- ✓ Chloride deposition is not expected to change dramatically in the future.

Corrosion of Carbon Steel after One Year of Exposure (Model 2)

Corrosion after 1 year of exposure (μm)	SO_2 (μg/m^3)	RH (%)	T (℃)	DCl (μg/m^3)	Increase in corrosion rate due to increased temperature (%)
3.56	1	60	11	60	0.6
3.58	1	60	13	60	
3.57	1	75	11	60	0.6
3.59	1	75	13	60	
55.90	1	60	11	300	7.8
60.28	1	60	13	300	
56.19	1	75	11	300	7.8
60.57	1	75	13	300	

Notes:

✓ The expected increase of 2 ℃ in temperature can have a significant negative impact on steel corrosion in environments with a high chloride concentration.

Models' Adjustment

Models 1 and 2 can be adjusted to the location of interest based on measurements from:

- ✓ the computer vision system on the extent and depth of corrosion damage
- ✓ the Ground Penetration Radar (GPR) on the depth of corrosion damage

Corrosion of Rebars in Reinforced Concrete

- There is a **number of models** relating surface crack width to corrosion depth in rebars

Proposed Model by Andrade et al. (2010):

$$\boldsymbol{w(t) = k\left(\frac{x'(t)}{c \times \Phi_o}\right)}$$

where:

$\boldsymbol{w(t)}$: is the crack width (opening) at time $\boldsymbol{t}$ (in mm)

$\boldsymbol{x'(t)}$: is the corrosion penetration at time $\boldsymbol{t}$ (in mm)

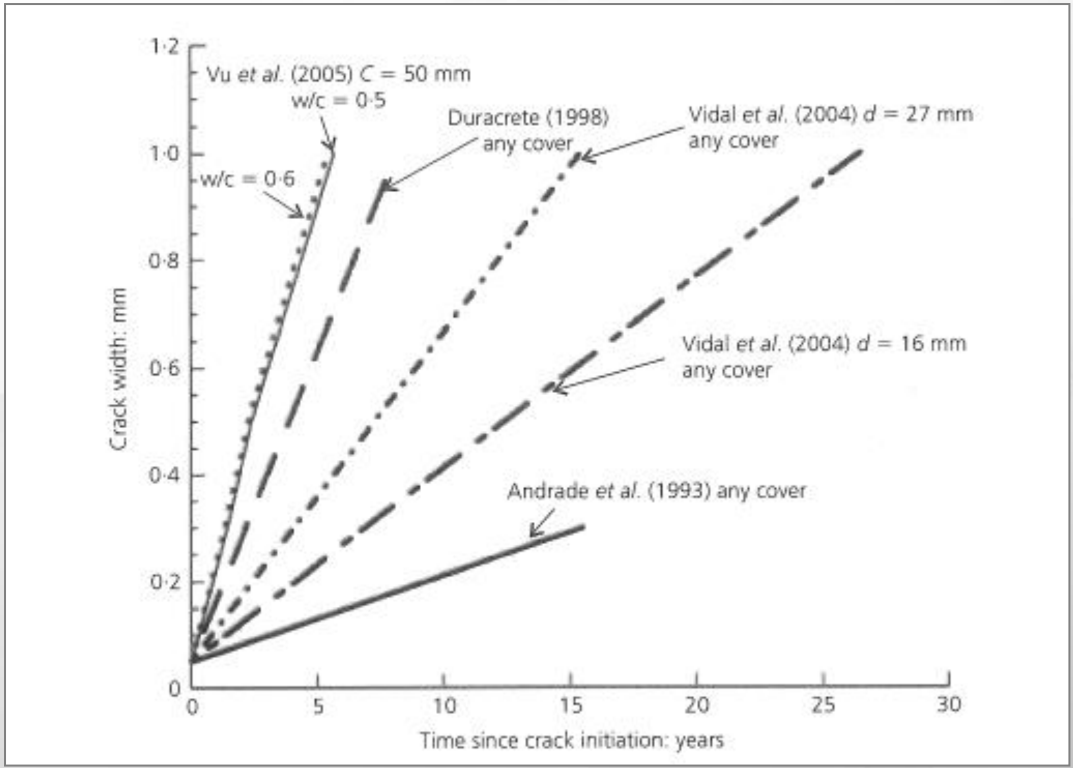
$\boldsymbol{k}$: is a factor of proportionality without dimensions that has a mean value of 9.5

$\boldsymbol{c}$: is the concrete cover (in mm)

$\boldsymbol{\Phi_o}$: is the original rebar diameter (in mm)

- By measuring $\boldsymbol{w}$, one can obtain $\boldsymbol{x'}$ and then the remaining rebar cross-section.

Comparison of Crack Propagation Models



where**:**
c: depth of concrete cover
w/c: water to cement ratio
d: rebar diameter
Corrosion rate: 1 μA/cm2

Note:

- Several future measurements of crack widths by the RPAS can help in selection of the most appropriate model.

Impact of CC (changes in temperature, relative humidity, CO_2 concentration) on the Corrosion of Reinforcing Steel Bars

Effect of CC on RC structures, regarding the carbonation ingress process (JRC, 2020)

Reference	Assumptions	Estimated value of carbonation depths by year 2100
Talukdar et al. (2012)	(a) increasing mean annual temperature (b) increasing duration of the hot season (c) constant RH over time and (d) increasing concentration of CO_2	Increase by 45%
Talukdar & Banthia (2013)	(a) time-dependent temperature	Increase between 27% and 45%
Saha & Eckelman (2014)	(a) increasing temperatures, (b) increasing concentrations of CO_2	Increase by 40%
Peng & Stewart (2014)	(a) CO_2 concentration (b) Local temperature and (c) RH variable over time	Increase by 45%
Mizzi et al. (2018)	(a) Increasing CO_2 concentration, and (b) Increasing temperatures	Increase up to 40%

Carbonation Depth

Proposed Model by Yoon et al. (2007):

$$X_c(t) = \sqrt{\frac{2f_T(t)D_{CO_2}(t)}{a} K_{urban} \int_{2000}^{t} CO_2(t)dt} \left(\frac{1}{t-1999}\right)^{nm}, \ t \geq 2000$$

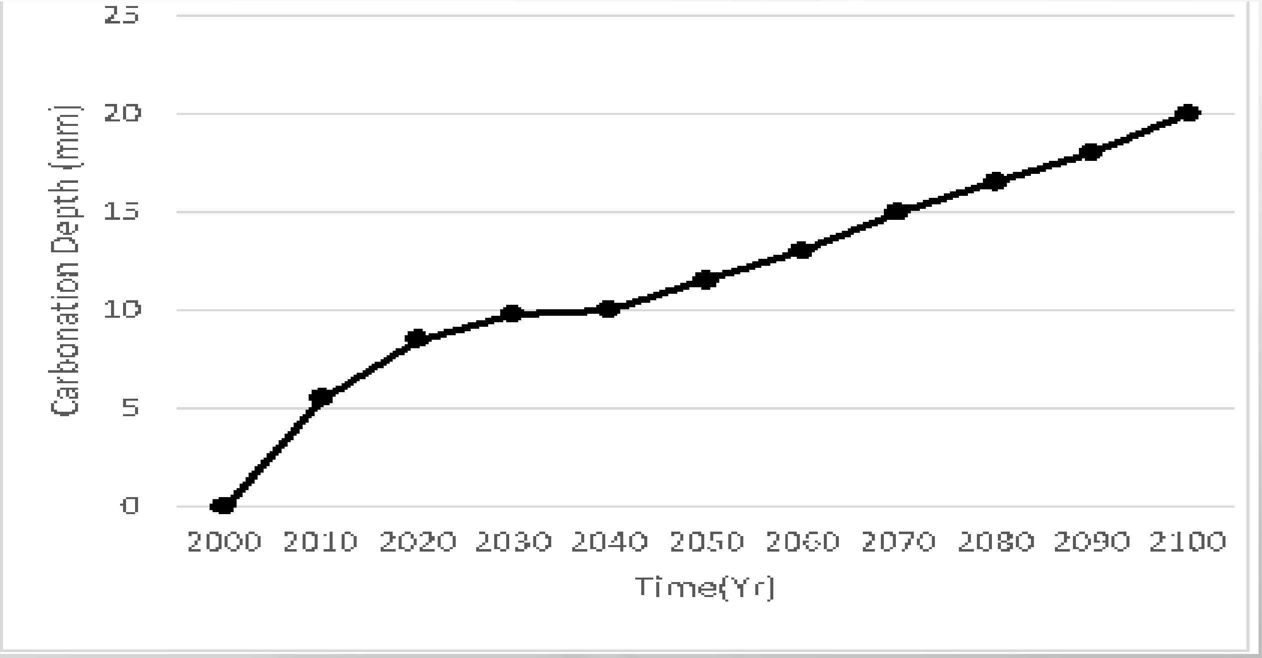
where:

- $X_c(t)$: is the carbonation depth at time t (in cm)
- $CO_2(t)$: is the time-dependent mass concentration of ambient CO_2 (in 10^{-3}kg/m^3)
- $D_{CO_2}(t)$: is CO_2 diffusion coefficient of concrete
- K_{urban}: is a factor to account for increased CO_2 levels in urban environments

Note:

The model does not account for differences in Temperature or Relative Humidity (RH)

Carbonation Depth as a Function of Increased CO_2 Concentration in the Atmosphere



Assumptions:

- Temperature=20^0C
- RH=65%
- Carbonation concentration will change as predicted in the pessimistic A1F1 scenario in IPPC, 2007

Discussion on Table & Figure

- ❖ The values in the Figure are more pessimistic than those in the Table
- ❖ According to Figure, the carbonation depth after 100 years of exposure will be less than 20mm when bridge depth cover is at least 50mm (or 5 cm).
- ❖ Based on the Arrhenius Law (used to model the effect of temperature on diffusion coefficient):
  - ✓ An increase of 2 ℃ in temperature will increase the diffusion coefficient by 12% and the values of carbonation depth by 3.464 (the square root of 12) based on equation proposed by Yoon et al. (2007)
  - ✓ Although the carbonation depth after 100 years of exposure will be 0.2 cm x 3.464=0.693 cm (meaning a huge increase), that number is far lower than the concrete cover

Impact of Climate Change on Chlorination-Induced Corrosion of Reinforcing Steel Bars

- The chloride concentration at a given depth depends on temperature and RH

Effect of CC on RC structures, regarding the chlorine ion ingress process (JRC, 2020)

Reference	Assumptions	Estimated value of chlorine-induced depths by year 2100
Xie et al. (2018)	(a) increasing temperature	Increase between 6% and 15%
Khatami & Shafei (2017)	(a) increasing temperature (b) Decreasing, constant or increasing RH (c) Increasing surface chloride concentration	Increase by 37%
Saha & Eckelman (2014)	(a) increasing temperatures, (b) increasing concentrations of CO_2	Increase by 12%
Peng & Stewart (2014)	(a) increasing temperatures and length of hot periods (b) increasing RH	Structure lifetime reduction ranging from 2% to 18%

- The studies show that the effect of CC on the RC structures affected by chlorination-induced corrosion is lower than in the case of carbonation, but still considerable

Impact of Climate Change in the Presence of Both Chlorination and Carbonation

- There are no studies that evaluate the impact of climate change in the present of both carbonation and chlorination.

Conclusions

- There is a need for accurate mathematical models accounting for the effects of CC and specifically the changing temperature, RH and CO_2 levels on material degradation.

- Based on the results of RESIST project:
  - ✓ The expected increase of 2 ℃ in temperature can have a significant negative impact on steel corrosion only in environments with a high chloride concentration

THANK YOU!

Any Questions?

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