

ASSESSMENT AND SERVICE LIFE UPDATING OF EXISTING TUNNELS

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ABSTRACT

This paper highlights the durability assessment (re-design and update) of an existing railway tunnel. This new approach, which has in general been developed within the European Brite-Euram research project DuraCrete¹ and has furthermore been improved within the European research project DARTS², enables the assessment linked to durability considerations of reinforced concrete structures over its service life related to limit state formulations. For the re-design and the update a new full-probabilistic method is being applied, taking tunnel specific conditions into account to assess the reliability of the tunnel lining against carbonation induced corrosion. This design approach has been used first for a bored tunnel construction in The Netherlands, cp. Gehlen and Schiessl³.

1. INTRODUCTION

Main elements of the service life design of new structures are: Identification of relevant and operational limit states, appropriate deterioration modelling, statistical quantification of material and environmental variables. Relevant information with regard to these items can be summarised and documented for each treated element in a so-called “birth certificate”.

As for existing structures detailed information issued within a “birth certificate” usually does not exist, relevant information has to be collected from drawings, tender documents, weather stations, inspections, and other possible sources. Based on the quantification of the collected data the re-design can be carried out. The result of this calculation gives information about the reliability resp. failure probability of the considered element for example against carbonation induced corrosion over its service life.

To improve the precision of the re-design the calculation can be updated by incorporating inspection data attained from the structure. In the considered case the information of measured carbonation depth, measured after 15 years of exposure has been used to demonstrate the updating procedure and its influence on the calculated reliability resp. failure probability. Furthermore an assessment based on this calculation result has been carried out to derive information if repair or maintenance action is needed to provide a sufficient reliability over service life according to the requirements given in the EC 1⁴.

2. STRUCTURE AND DECISION PROBLEM

The tunnel structure, which is part of a railway express connection, has been build with reinforced concrete. The overall length of the tunnel amounts to $l_{\text{tunnel}} = 1100$ m.

The respective limit state equation describing the probability that depassivation takes place is given in Equation (1).

$$p\{\text{failure}\} = p_f = p\{d_c - x_c(T) < 0\} \quad (1)$$

p_f : failure probability [%]

d_c : concrete cover [mm]

$x_c(T)$: carbonation depth at the time T [mm]

T: target service life [a], here T = 100 a

The variables d_c and $x_c(T)$, which have to be quantified for the full-probabilistic service life design are represented by the following subfunctions:

$$d_c = d_{c,\text{meas}} + \Delta d_c \quad (2)$$

$d_{c,\text{meas}}$: non-destructively measured concrete cover [mm]

Δd_c : uncertainty of non-destructive measurement [mm]

$$x_c(T) = x_{c,0}(T) + \varepsilon_{x_c} \quad (3)$$

ε_{x_c} : error term considering the non-uniform carbonation process in space [mm]

$$x_{c,0}(T) = \sqrt{2 \cdot k_e \cdot k_c \cdot (k_t \cdot R_{\text{ACC},0}^{-1} + \varepsilon_t) \cdot C_s \cdot \sqrt{T} \cdot W(T)} \quad (4)$$

k_e : variable considering the influence of environment (e.g. realistic moisture at concrete surface during use; RH_{real}) on the effective inverse carbonation resistance [-]

$$k_e = \left(\frac{1 - \left(\frac{RH_{\text{real}}}{100} \right)^{f_e}}{1 - \left(\frac{RH_{\text{ref}}}{100} \right)^{f_e}} \right)^{g_e} \quad (5)$$

RH_{real} : relative humidity of the carbonated layer [%]

RH_{ref} : reference humidity [%]

f_e : exponent [-]

g_e : exponent [-]

k_c : variable taking into account the influence of curing of the effective carbonation resistance [-]

$$k_c = a_c \cdot t_c^{b_c} \quad (6)$$

a_c : parameter of regression [-]

b_c : exponent of regression [-]

t_c : period of curing [d]

k_t : model variable considering the influence of test method (translation of accelerated (ACC) to natural (NAC) test results) [-]

$R_{\text{ACC},0}^{-1}$: inverse effective carbonation resistance of dry concrete, determined at a certain point of time t_0 on specimens with the accelerated carbonation test ACC in $[(\text{mm}^2/\text{a})/(\text{kgCO}_2/\text{m}^3)]$

ε_t : error term considering inaccuracies which occur conditional on the ACC test method $[(\text{mm}^2/\text{a})/(\text{kgCO}_2/\text{m}^3)]$

C_s : CO_2 -concentration at the surface $[\text{kgCO}_2/\text{m}^3]$

W: weather function considering the influence of meso climatic conditions (re-wetting) [-]

$$W = \left(\frac{t_0}{t} \right)^{\frac{(p_{SR} \cdot ToW)^{b_w}}{2}} = \left(\frac{t_0}{t} \right)^w \quad (7)$$

t_0 : time of reference [a]

w: weather exponent [-]

ToW: time of wetness [-]

$$ToW = \frac{\text{days with rain if all } h_{Nd} \geq 2.5 \text{ mm per year}}{365} \quad (8)$$

p_{SR} : probability of driving rain [-]

b_w : exponent of regression [-]

To describe the process of carbonation and the concrete cover with its variability statistical information is required to perform a full-probabilistic service life re-design. The stochastic quantification of the variables are given in Table 1. The listed variables in this table have been taken from the Equations (2) till (8).

Variable	Unit	Distribution	Mean Value	Standard Deviation	Background information and quantification according to
ε_{x_c}	mm	normal	0	2.0	Hergenröder ⁵
k_e	RH _{real,WS}	%	beta	m = 78; s = 15; a = 40, b = 100	
	RH _{ref}	%	constant	65	-
	g_e	-	constant	2.5	-
	f_e	-	constant	5.0	-
k_c	b_c	-	normal	-0.567	0.024
	t_c	d	constant	2	-
k_t	-	normal	1.25	0.35	DARTS ⁶
$R_{ACC,0}^{-1}$	(mm ² /a)/(kgCO ₂ /m ³)	normal	3943	1577	DARTS ⁶
ε_t	(mm ² /a)/(kgCO ₂ /m ³)	normal	315.5	48	DARTS ⁶
C_s	kgCO ₂ /m ³	normal	$8.2 \cdot 10^{-4}$	$1.0 \cdot 10^{-4}$	DARTS ⁶
T	a	constant	100	-	client requirement based on EC 1 ⁴
W	ToW	-	constant	0	-
	b_w	-	normal	0.446	0.163
	p_{SR}	-	constant	0	-
	t_0	a	constant	0.0767	-
d_c	$d_{c, meas}$	mm	normal	47.5	18.8
	Δd_c	mm	normal	1.3	5.8

Table 1 List of stochastic variables influencing the duration of the initiation period (carbonation induced corrosion) of the tunnel.

In the following comments to the weather function will be given and furthermore it will be shown how the stochastic quantities of the concrete cover have been obtained.

3.1.1 Quantity of the weather function

The variables belonging to the weather function take the meso climatic condition due to wetting events of the concrete into account, cp. p_{SR} and ToW in Equation (7). As inside the tunnel rain events can be excluded, consequently the weather exponent equals to zero and therewith the value of the weather function is one. By doing so the possible appearance of condensation at tunnel walls is neglected, which would have a favourable effect on the predicted reliability, when modelling the initiation period.

As the accumulation of condensation water at tunnel walls or roofs can often only be observed at singular locations, a general consideration of condensation water within the service life calculation is considered to be inappropriate. Although this beneficial effect should not be taken into account in general, the influence of this possible event can be considered indirectly by incorporating inspection data within an update.

3.1.2 Quantification of concrete cover

The concrete cover has been measured with non-destructive testing equipment. In Figure 2 the result of the concrete cover measurements within one tunnel section is outlined. Within one cross section three areas have been measured with a grid pattern over 10 m in lengthwise direction. Within this example solely the critical area at the roof has been assessed.

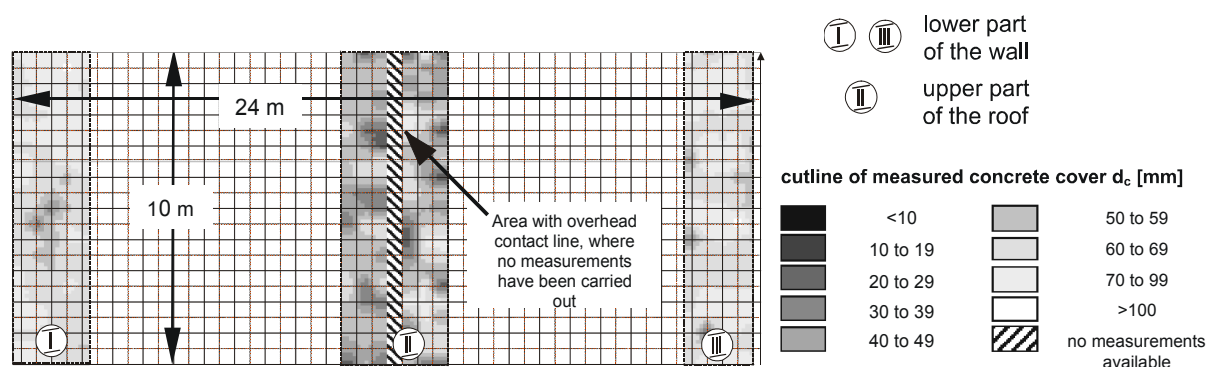


Figure 2 Measured concrete cover, illustrated at the winding-up of the tunnel lining (dashed line in Figure 1) with the critical area II (dotted line in Figure 1).

The evaluation of the measured data has been carried out with a software packet from RCP⁷. According to the statistical quantification the variable $d_{c,meas}$ is normally distributed with a standard deviation of $s = 18.8$ mm scattering around the mean value of $m = 47.5$ mm.

Further destructive measurement methods have been carried out (e.g. drilling cores) to determine inaccuracies of the non-destructive measured concrete cover. The result of this calibration is considered within the term Δd_c , which has been determined as a normal distributed variable with a standard deviation of $s = 5.8$ mm scattering around the mean value of $m = 1.3$ mm. This means, that in the considered case the mean value of the real concrete cover is slightly higher than detected with the non-destructive measurement technique. This systematic deviation between the non-destructive measured and the real concrete cover is due to the fact that ferrous aggregates have been used for the concrete mix.

3.2 Mean Value Prediction and Measurement Data of The Carbonation Depth

Based on mean values of the quantified variables it is possible to predict the time dependent process of carbonation (described by Equation(3)) with an ordinary calculator. The result of such a calculation is given in Figure 3.

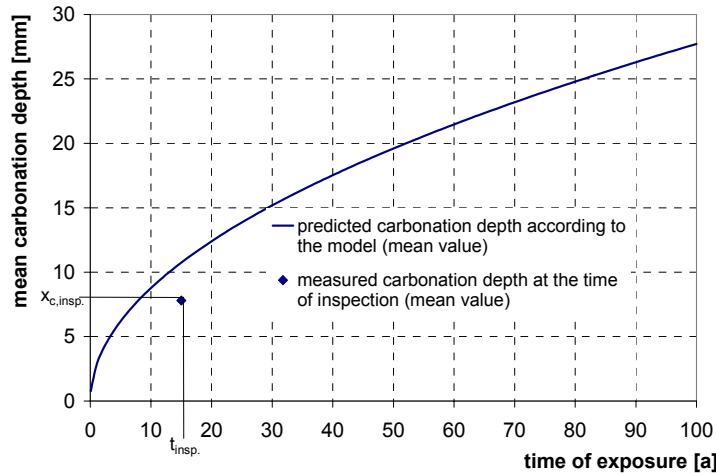


Figure 3 Predicted mean time dependent progress of carbonation, calculated according Equation (3) with mean values given in Table 1.

During inspection carbonation depths have been measured at the considered concrete surface. Beside the mean value of the predicted carbonation depth in Figure 3 also the mean value of the carbonation depth measured after 15 years of exposure ($t_{\text{insp.}}$) is outlined. It can be observed that the mean value of the measured carbonation depth ($x_{c, \text{insp.}} = 7.8 \text{ mm}$) is lower than the predicted carbonation depth ($x_c = 10.7 \text{ mm}$) by the time of inspection.

One reason for this deviation is due to the fact that especially for the weather function an estimation on the safe side has been chosen, assuming that no condensation water will accumulate at the considered concrete surface.

3.3 Full-probabilistic calculation

3.3.1 Re-design

To determine the limit state based failure probability resp. reliability the limit state function (Equation(1)) has to be analysed in a probabilistic mode, hereby taking all load and resistance variables with their variability into account. This re-design according to Equation (1) has been realised with a software package provided by RCP⁷. The time dependent increase of the predicted failure probability p_f and the respective decrease of the reliability index β over an exposure period of 100 years is illustrated in Figure 4.

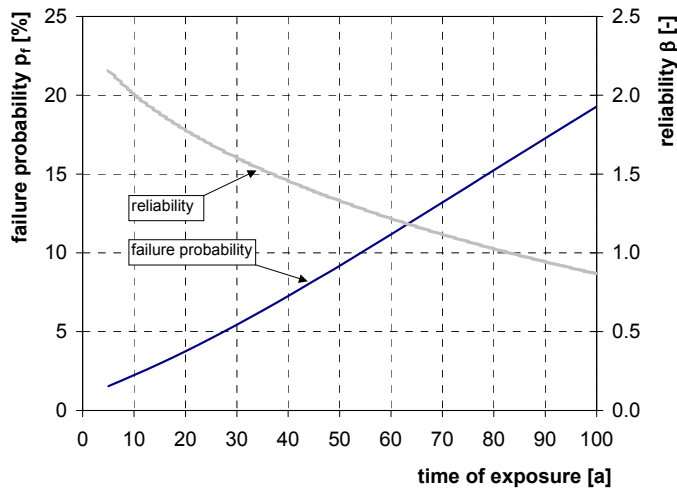


Figure 4 Re-design; time dependent progress of limit state based failure probability p_f [%] and the reliability index β [-]

After 100 years of exposure the limit state based failure probability reaches $p_f = 19$ %. This failure probability corresponds to a reliability index of $\beta = 0.9$, cp. Figure 4.

3.3.2 Update

Through incorporation of the inspection data, which has been attained from the structure, it is possible to update the service life calculation, hereby considering the deviation of the predicted and the measured carbonation depth after 15 years of exposure. The following Equation (9) shows the equality constraint which is required to realise the update.

$$x_{c,insp.} = \sqrt{2 \cdot k_e \cdot k_c \cdot (k_t \cdot R_{ACC,0}^{-1} + \varepsilon_t) \cdot C_s} \cdot \sqrt{t_{insp.}} \cdot W(t_{insp.}) + \varepsilon_{x_c} \quad (9)$$

$t_{insp.}$: time of inspection [a], here: 15

$x_{c, insp.}$: carbonation depth at time of inspection [mm], here: logN, $m = 7.8$, $s = 3.5$

In consequence of this additional equation the list of stochastic variables (cp. Table 1) expands with two supplementary variables. Taking the inspection data into consideration the update of the service life analysis has been accomplished, cp. Figure 5.

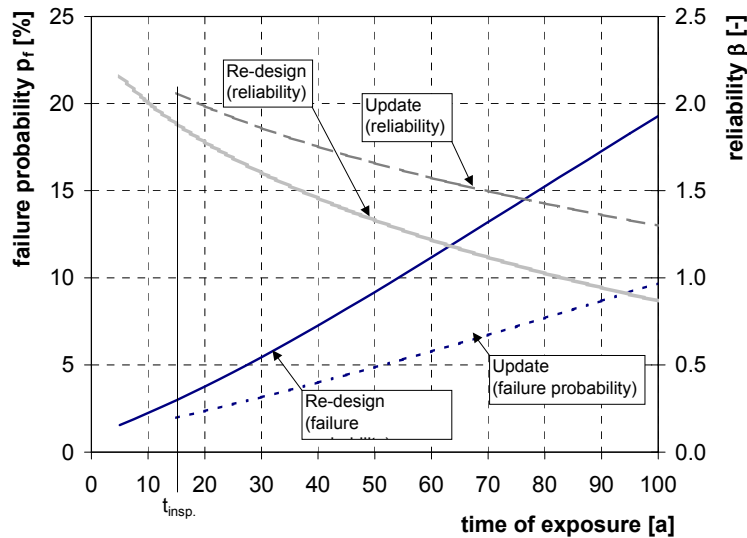


Figure 5 Re-design and update; time dependent progress of limit state based failure probability p_f [%] and reliability index β [-]

From Figure 5 it can be observed, that by considering the inspection data within an update the reliability at the end of service life $T = 100$ years increases from $\beta = 0.9$ to $\beta = 1.3$ and the respective failure probability decreases from $p_f = 19\%$ to $p_f = 9.7\%$.

The deviation between both calculations (re-design and update) is due to the fact, that not only the uncertain expected mean value of the carbonation depth after 15 years of exposure was detected to be lower but also the variation of the inspection result was lower than predicted. Both circumstances have a favourable effect on the reliability.

4. ASSESSMENT

Furthermore the investigated results of the full-probabilistic service life update can be compared with the requirements given in the EC 1⁴, cp. Table 2.

limit states	target reliability β (at the end of service life)	calculated reliability β (at the end of service life)
serviceability limit state	1.5 (irreversible)	1.3

Table 2 Indicative values for the target reliability according to EC 1⁴ and calculated/predicted reliability

By comparing the result of the update (calculated reliability at the end of service life) with the requirement for a serviceability limit according to the EC 1⁴ it can be concluded, that extra repair/maintenance action (coating or other protective measures) may be necessary to provide a sufficient reliability against carbonation induced corrosion over a service life of $T = 100$ a.

By incorporating inspection data determined after 15 years of exposure the reliability at the end of service life is upgraded from 0.9 to 1.3. Therefore it might be reasonable to carry out yet another inspection (to be carried out till 70 years of exposure, as up to then $\beta_{\text{update}} > 1.5$) to verify the need for extra repair/maintenance.

5. CONCLUSIONS

A full-probabilistic service life re-design for an existing tunnel structure was presented, for an area, in which low concrete covers have been measured. Furthermore an update has been carried out, by considering inspection data. Hereby it can be observed that the predicted reliabilities within the update increase compared to respective the re-design result. One reason for this deviation is due to the fact that within the re-design estimations for some variables on the safe side have been chosen. By integrating inspection results into the calculation procedure the actual behaviour of the structure within the environment can be considered directly and therewith improving the quality of the calculation.

6. REFERENCES

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