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Predicting the Service Life of Concrete Bridges Based on Quantitative Research

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Abstract: **A new method is proposed that will help predict the remaining service life of concrete bridges based on quantitative deterioration research. It is suggested that for a given degree of damage (stage) and corresponding environmental and bridge design factors, there is only one time value. In that way it is possible to calculate the deterioration rate for given environmental and bridge design factors shared by many different bridges. The method can be used to calculate the key parameters for corrosion deterioration, thereby enabling the prediction of the remaining service life of a bridge using DuraCrete deterioration models.**

Keywords**: Concrete bridge, deterioration model, reinforcement corrosion, service life prediction.**

I. Introduction

For several years now Latvia's bridges have not received necessary maintenance and repairs. As a result, 56 % of the country's bridges are in poor or very poor technical condition [1]. One of the main problems is the early deterioration of reinforced concrete bridges. Lack of concrete bridge durability compared to the expected life of these structures is an issue of concern in most countries, where most development has taken place during the last century [2], [3]. Due to the lack of funds, optimal planning of maintenance and repair is becoming increasingly important; therefore, it is necessary to develop methods of predicting the performance of reinforced concrete bridges in the future.

The Latvian Department of State Roads currently manages 938 bridges, of which 94 % are reinforced concrete bridges. Most of them were built between 1960 and 1980. Regular bridge inspections show that about 60 % of in-service reinforced concrete beam bridges have extensive damage to reinforced concrete. Reinforcement corrosion is the most common type of reinforced concrete bridge damage in Latvia.

To predict a bridge's service life, it is necessary to model the interaction progression of environmental and bridge structure design factors [4]. The environmental impact on the service life of a concrete bridge can be determined by estimating the values of the amount of deterioration and the corresponding environmental parameters.

This paper outlines a method of assessing the technical condition of concrete bridges with respect to the progression of reinforcement corrosion deterioration, taking into account different environmental and bridge design factors and thereby enabling the remaining service life of concrete bridges to be predicted. Service life is determined empirically, by assuming that the progression of deterioration does not change under identical environmental and bridge design factors.

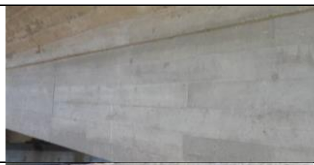
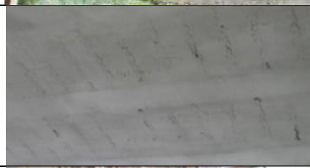
TABLE I

CLIMATE LEVELS AND ASSOCIATED DIFFERENT ENVIRONMENTAL AND STRUCTURAL DESIGN FACTORS

	Macro level (general descriptions)	**Surface level (detectable by visual inspection)**	**Micro level (model parameters)**
Load – environment	Air temperature. Relative humidity of the air. Duration of sunshine. Wind speed and direction. Driving rain. Amount of precipitation.	Surface exposed to precipitation. Surface protected from precipitation. Splash zone. Water trough zones (due to deteriorated membrane or expansion joints). De-icing salt impact. Road environment at bridge (strategy of use of de-icing salt, maintenance class, traffic intensity).	Amount of CO_2 in concrete surface. Weather/wetting parameters. Surface chloride concentration. RH level in concrete.
Resistance – structure design, materials	Bridge geographical location – distance from sea. Bridge type (bridge over river, overpass).	Surface position (vertical, horizontal, upwards or downwards). Surface position depending on cardinal points (North, East, South, West). Surface overhang. Surface distance from the road. Surface position depending on direction of traffic.	Concrete cover. Resistance of carbonation. Chloride diffusion coefficient. Initial chloride concentration. Water / binder ratio. Concrete strength. Permeability of concrete.

TABLE II

STAGES OF REINFORCED CONCRETE DETERIORATION

Stage	Description	Example
0	Initiation phase – no visible signs of reinforcement corrosion and no signs of leaching corrosion or concrete products.	
1	Leaching of corrosion or concrete products through micro cracks.	
2	Concrete cracking due to reinforcement corrosion (secondary reinforcement).	
3	Concrete delamination (secondary reinforcement).	
4	Spalling of concrete (secondary reinforcement).	
5	Reduction of cross-sectional area of reinforcement due to corrosion (secondary reinforcement).	
6	Concrete cracking due to reinforcement corrosion (primary reinforcement).	
7	Concrete delamination (primary reinforcement).	
8	Spalling of concrete (primary reinforcement).	
9	Reduction of cross-sectional area of reinforcement due to corrosion (primary reinforcement).	

In-depth research on reinforced concrete structure deterioration due to environmental conditions began in the early 1980s along with the development of the European Standard EN 206. The development of deterioration and its impact on service life was first defined by K. Tuutti [5]. Deterioration progression models with highly relevant practical applications were developed within the EU-funded research project DuraCrete [6], [7], [8]. During the last 10 years, the models developed for the DuraCrete project have been commonly used in the studies on the durability of bridge structures all around the world. The corrosion and deterioration of reinforced concrete structures due to the use of de-icing salts on roads have been widely studied in Sweden in research conducted by A. Lindvall [9] and G. Fagerlund [10], [11]. The methods applied and results obtained from these studies are pertinent to Latvia's bridges because of the similarity of the road environments.

II. The Methodology of the Quantitative Research

The mutual interaction between environmental conditions and bridge design factors can be categorized into three levels: the macro level, the surface level and the micro level (Table I).

Deterioration and its degree are direct consequences of the interaction of environmental conditions and design factors at the micro level. Therefore, it is necessary to obtain data for the parameters that characterize these interactions in order to make accurate service life forecasts. The progression of deterioration at the micro level is described by deterioration models, and the parameters for these models cannot be acquired by visual inspection; detailed material investigation on site or at the laboratory is required. Some parameter values, depending on conditions, also are recommended in the literature [7], [12], [13].

The surface level is characterized by environmental conditions that are constant over the whole or part of the defined surface, and are detectable by visual inspection. Environmental conditions that are considered constant at the surface level can be variable at the micro level, because, for example, it is impossible to visually detect variations in humidity, although this is a significant precondition for deterioration. This explains the uneven progression of deterioration on one defined surface. The deterioration preconditions at the surface level are defined by environmental conditions (precipitation, splashes, sunshine exposure, etc.) and bridge design factors (surface position, surface distance from the road, shape, cover depth, etc.). By determining the stage of deterioration for a structure affected by such various conditions, it is possible to identify the preconditions that characterize the progression of deterioration and calculate a bridge's approximate service life.

The macro level describes the general environmental and climatic conditions, descriptive data about which can be collected from meteorological stations. The macro level also describes the geographical location of the structure. At this level one can characterize, for example, the average service lifetime of different types of bridge structures in Latvia.

The data acquisition methodology consists of three blocks:

- Block No. 1. Bridge design. Bridge design characteristics, material properties, surface classification and location.
- Block No. 2. Load. Environmental conditions and quantification of its parameters. Includes general, local and other influences.
- Block No. 3. Defects/resistance. The characteristic values and quantification of deterioration.

By quantifying these parameters and each factor's relevance it is possible to determine the quantitative values of deterioration rates.

The surfaces of bridge structures are classified depending on the environmental conditions affecting them and the amount of damage, as well taking into account the design and material properties. It is assumed that for one surface the environmental conditions and design/material properties are uniform over the whole surface. For example, the side wall surfaces of beams near piers are exposed to water troughs, so a beam's side surface should be divided into three different surfaces, each subject to different environmental conditions.

Deterioration is characterized by its development stage and the amount expressed as a surface area. The stages of deterioration for one defined surface are determined visually by distinguishing the dominant and maximum stages. By determining the stage of the deterioration the primary and secondary reinforcement can be distinguished. The stages of deterioration and their characteristics are shown in Table II.

The amount of the dominant deterioration stage can be determined visually from the surface area as widespread or medium-spread, and the amount of the maximum deterioration stage of the total surface area can be determined as local, medium or widespread.

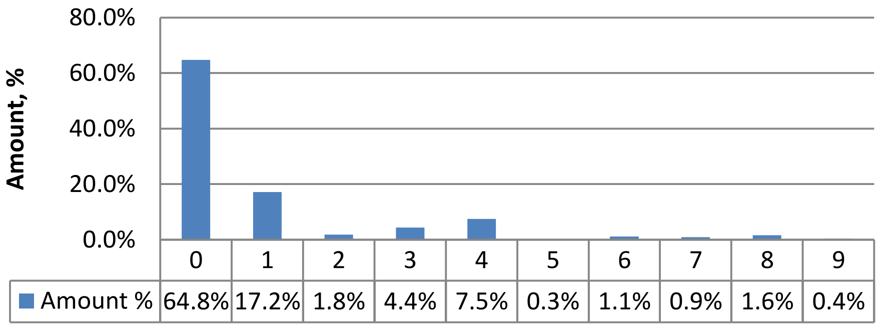


Fig. 1. Distribution of reinforcement corrosion damage by stage and amount.

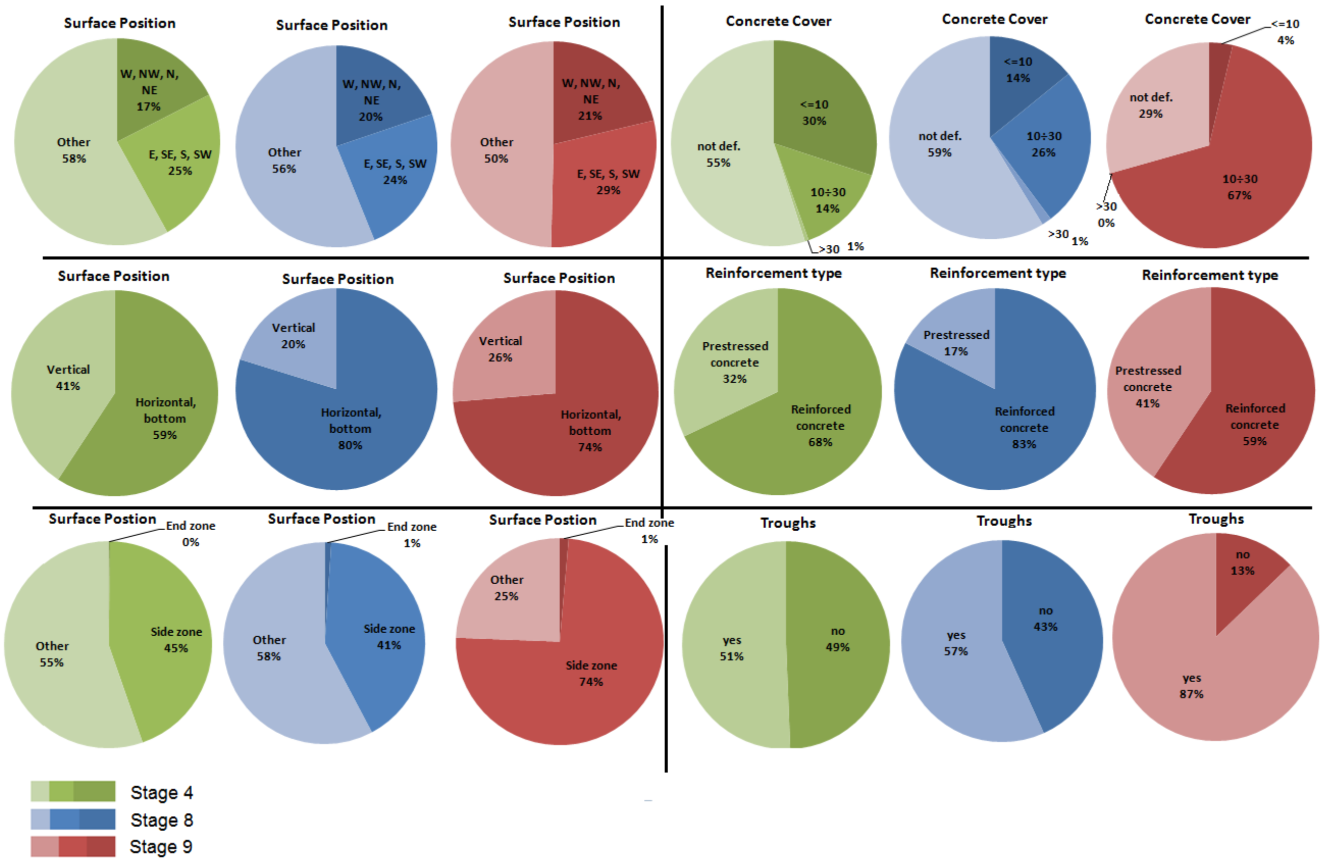


Fig. 2. The importance of different factors.

III. Results and Discussion

By using this data acquisition methodology, information on reinforcement corrosion deterioration has been collected from 120 bridges all over Latvia. In total, 922 deterioration characteristics were obtained from bridges, most of which are located in Riga. None of the bridge structures studied has received repairs that would affect the development of continuous deterioration.

Because most of the existing bridges in Latvia were built between 1960 and 1980, most of the information obtained will concern these bridges. The collected data were acquired from bridge inspections that were carried out between 1995 and 2010, which means that there could be one time period for bridges whose ages differ by 10 to 15 years.

One reinforced concrete structure of a bridge can have any deterioration stage regardless of its age. However, taking into account various design factors and environmental conditions, as well as the variation of the stages, it is possible to obtain information on the rate of deterioration.

The total amounts of deterioration distinguished by the stages are displayed in Figure 1. The deterioration amount makes up part of the total surface area. As the deterioration stage advances, the deterioration amount decreases. Of the researched bridges, no signs of damage were found (Stage 0) on 64.8 % of the surface area, while secondary reinforcement defects made up 14 % of the surface area (Stages 2, 3, 4 and 5).

Primary reinforcement defects (Stages 6, 7, 8 and 9) made up 4 % of the surface area.

The importance of several factors for different deterioration stages are displayed in Figure 2.

The results show the characteristic parts of a bridge design in which one deterioration stage is possible. Deterioration is less likely to appear on structures which are stressed and not exposed to water troughs. Most of the deterioration that affects the service life of concrete bridges appears in local parts of the structures where the most aggressive microclimatic conditions form, causing and accelerating the deterioration of the reinforced concrete. The most common positions of reinforced concrete defects are at damaged expansion joints, edges of slabs, edge beams, bearings, bridge beam soffits without dripnoses, pier/beam/slab horizontal surfaces, and the corners and edges of the bridge. The shape and design of the structure affects the location and severity of the critical nodes.

A combination of factors and corresponding deterioration stages characterize the specific environmental conditions and structural design interaction conditions, and different surfaces of different bridges can have analogous factor combinations.

IV. Service Life Models – New Method

This paper describes a method of assessing the degree and amount of damage so that one can determine the rate of the deterioration depending on different environmental and design factors in order to make a service lifetime forecast for a bridge, based on the data obtained from visual inspections. Visual inspection is the easiest, most economical and most commonly used means of making a technical assessment of a bridge. One of the main shortcomings of visual inspection is the possibility of inconsistent documentation of deterioration degree and amount, which are usually determined based on the inspector's experience and subjective assessment. Inspection reports often include photos of the detected damage, so in that way the damage is accurately documented, but such information is difficult to use for quantitative statistical analysis and data processing [14], [15].

The main components of predicting residual service life of a bridge (Figure 3):

– defining the degree of deterioration (in stages), which can be determined by visual bridge inspection;
– defining the amount of deterioration (as an area on the surface), which can be determined by visual bridge inspection;
– defining the environmental conditions and bridge design factors;
– determining the service life for factor combinations at different deterioration stages;
– calculating the deterioration rate parameters;
– predicting the service lifetime based on factor combinations, deterioration stage and rates.

The limit state of a bridge can be used as one of the deterioration stages. The time value in years shows the age of the bridge at the time of inspection since its commissioning.

TABLE III

THE DETERMINATION OF DETERIORATION AMOUNT

Max / Dom	Widespread	Medium	Local
Widespread	100 % dominant	70 % dominant 30 % maximum	85 % dominant 15 % maximum
Medium	–	50 % dominant 50 % maximum	50 % dominant 25 % maximum

Depending on the combination of factors, the deterioration amount and the corresponding time of stage onset can be acquired from the database.

Depending on the results, it is possible to determine the possibility of deterioration occurring in a specific structure. The factors are assumed to be independent of time.

Data for the concrete bridge reinforcement corrosion deterioration development:

– characterize the stage of deterioration at a specific time (i.e. the time of detection);
– do not describe the specific time at which the specific stage was reached;
– show the deterioration stage that has not yet been reached in a given time period.

A bridge's deterioration is characterized by its stage and the amount of surface area affected. For each such characteristic there is a matching time value and combination of factors. The amount of the deteriorated area is determined in accordance with Table III.

If one bridge structure surface is subjected to reinforcement corrosion and is assessed every year of its service life, then it is possible to acquire accurate year-by-year information on the stages and amount of deterioration over time (Figure 4). By defining the combination of environmental and structural design factors for a specific surface, it is possible to determine the preconditions for the causes and rate of the development of deterioration. It can be assumed that for each factor combination there is one deterioration model, which is characterized by the stages and rate of the development of reinforcement corrosion deterioration. The main characteristic of this model is the stage onset time, $T(n)$. Knowing the stage onset time for one combination of factors makes it possible to predict the stage onset time for other structures with the same combination of factors.

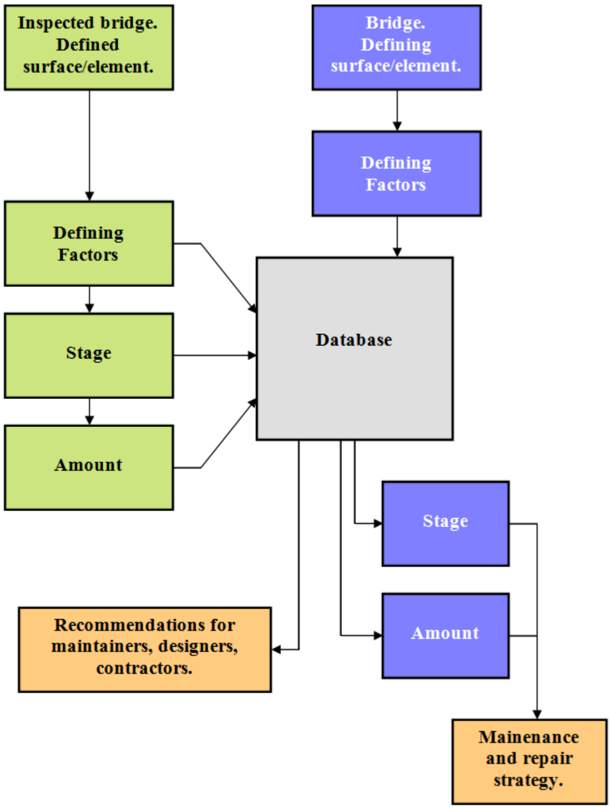


Fig. 3. Flow chart detailing the method of predicting concrete bridge service life.

If the inspection is carried out each year, then the onset time of the stage can be determined with a precision of 1 year, whereas if inspections are carried out three times or less in 10-year period, then the precision will be 3 to 10 years. By determining the stage onset time for one factor combination, the information can be acquired from more than one bridge if their elements have the same factor combinations; in that way greater precision can be achieved. Inspecting more bridges with the same factor combinations for the structure surfaces increases accuracy, and makes it possible to determine stage onset times with 1-year accuracy without carrying out inspections every year for every bridge. During a bridge inspection, the age of the structure at the time of inspection, the stage of deterioration and amount of deterioration are determined. The onset time values of the stage for one factor combination can be calculated by considering only the values lower than $-1\ Q$, i.e. $t<(-0{,}6745\ \sigma)$, to exclude the values that are determined during the end phase of the deterioration stage.

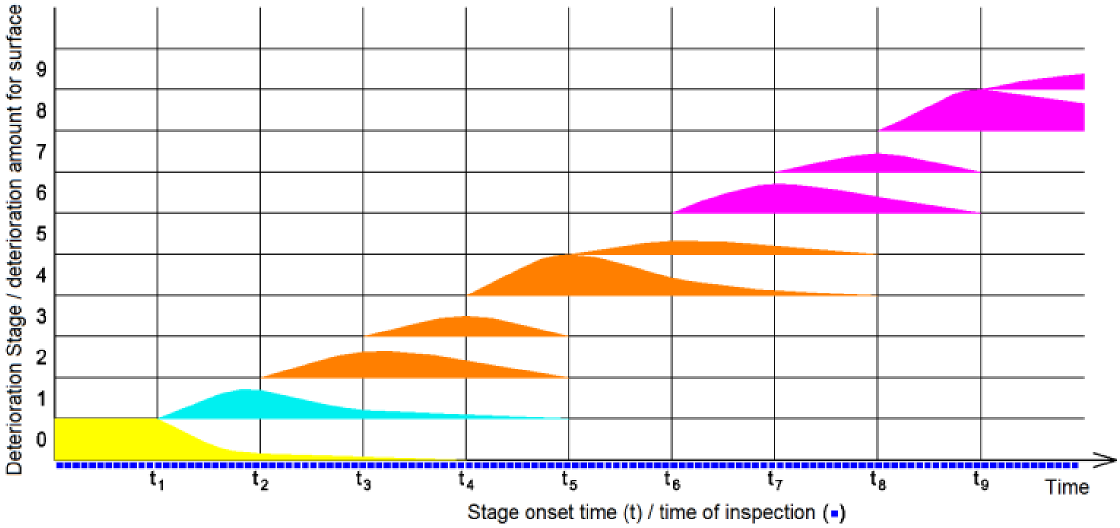


Fig. 4. Example of bridge deterioration through stages, by performing inspections each year.

Due to the heterogeneous environmental conditions at the micro climate level, the development of deterioration over one surface will never start at the same time. Initially the defects on a structure's surface start to appear in local areas and later expand over the entire surface area. Therefore, the designated maximum damage of a stage, marked as local damage, characterizes the beginning phase of the stage. As the deterioration expands, it reaches the medium phase (referred to as the medium amount of deterioration) and the end phase (indicated by widespread deterioration). In the end phase, or even earlier, the next deterioration stage can also start to develop initially as local damage. It can therefore be assumed that performing bridge inspections identifies not only the stage and the amount of deterioration, but also the phase of the current stage of deterioration. By determining the onset time of a stage, greater weight should be put on deterioration with locally detected defects (the maximum deterioration stage of the surface).

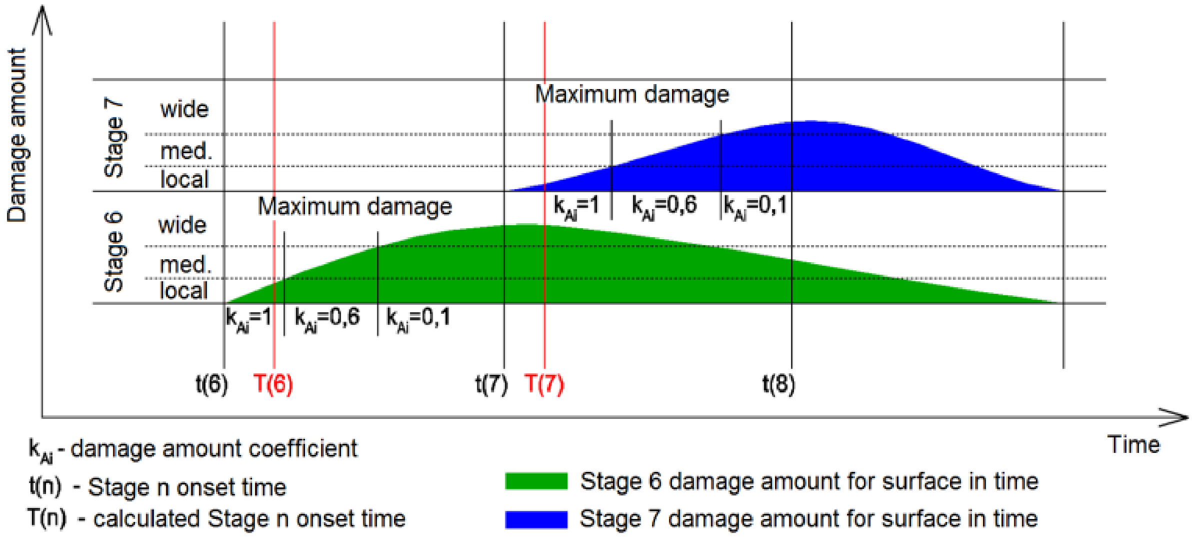


Fig. 5. Determination of time value $T(n)$.

The stage n onset time $T(n)$ for the corresponding factor combinations can be calculated by taking into account the determined time values t and deterioration amount values A_i, as well as the deterioration phase, which is characterized by coefficient k_{Ai}. The values of coefficient k_{Ai} depend on the designations "local", "medium" and "wide".

The stage onset time is determined using this mathematical expression:

$$T(n) = \frac{\sum_i t_i(n) A_i(n) k_{Ai}(n)}{\sum_i A_i(n) k_{Ai}(n)},$$

where

$T(n)$ is stage n onset time;

t_i is one time measurement for the corresponding stage;

$$k_{Ai} = \begin{cases} 1.0 \text{ (local)} \\ 0.6 \text{ (medium)} \\ 0.1 \text{ (wide)}. \end{cases}$$

V. Concrete carbonation – initiation phase

The calculation of parameters for the initiation phase of carbonation-induced reinforcement corrosion is performed by using the DuraCrete carbonation model [7], [12]:

$$\left.\begin{aligned} x_c(t) &= \sqrt{2\Delta C_S R_{FC}^{-1}}\sqrt{t}W \\ x_c(t) &= x_{\text{cover}} \end{aligned}\right\} \Rightarrow R_{FC}^{-1} \qquad (1)$$

where
$x_C(t)$ is the concrete carbonation depth;
ΔC_S is the content of CO_2 in the air;
R_{FC}^{-1} is the resistance of the concrete carbonation;
t is the time;
W is the parameter describing weather (surface exposed to water);
x_{cover} is the concrete cover.

Calculating the parameters for the initiation phase of carbonation, it is assumed that carbonation has reached the reinforcement, which is the onset of deterioration Stage 2 (secondary reinforcement) or Stage 6 (main reinforcement), and therefore the value of $x_c(t)$ should be compared to the cover depth x_{cover}.

The concrete carbonation resistance parameter R_{FC}^{-1} is calculated on the basis of the parameters indicated in Table IV.

TABLE IV
PARAMETER VALUES FOR CALCULATING CONCRETE CARBONATION RESISTANCE

Parameter	Designation	Assumed value
Concrete cover	x_{cover}	up to 10 mm. from 10 mm to 30 mm. above 30 mm.
CO_2 content in the ambient air	ΔC_S	0,00082 [kgCO_2/m^3].
Weather parameter	W	No water exposure (dry environment): W = 1. Troughs (the cyclic wet and dry environment): W = 3.24.
End time of initiation phase	T	Stage 2 onset time: T(2). Stage 6 onset time: T(6).

VI. Accumulation of chlorides – initiation phase

The chloride accumulation process is modeled using the following DuraCrete model [7], [12]:

$$\left.\begin{aligned} C(x,t) &= C_i + (C_s - C_i)\cdot erf\left(1 - \frac{x}{\sqrt{tD_{FC}}}\right) \\ C(x_{\text{cover}},t) &= C_{crit} \end{aligned}\right\} \Rightarrow D_{FC} \qquad (2)$$

where
$C(x,t)$ is the chloride concentration at depth x, depending on the time t;
C_S is the surface chloride concentration;
C_i is the initial chloride concentration;
t is the time;
x_{cover} is the concrete coating thickness;
C_{crit} is the critical chloride concentration;
D_{FC} is the diffusion coefficient.

Calculating the parameters for the initiation chloride accumulation phase, it is assumed that the critical concentration of chlorides has reached the reinforcement, which is the onset of deterioration Stage 2 (secondary reinforcement) or Stage 6 (main reinforcement), so the value of $C(x,t)$ should be compared to the critical chloride concentration value C_{crit} at cover depth x_{cover} [16].

The chloride diffusion parameter D_{FC} is calculated on the basis of the parameters indicated in Table V.

TABLE V
PARAMETERS OF CHLORIDE ACCUMULATION FOR CALCULATING RESISTANCE

Parameter	Designation	Assumed value
Concrete cover	x_{cover}	up to 10 mm. from 10 mm to 30 mm. above 30 mm.
Initial chloride concentration	C_i	0.1 [%]
Surface chloride concentration	C_S	No exposure to precipitation: C_S = 2.0 %; Surface exposed to precipitation: C_S = 1.2 %.
Critical chloride concentration	C_{crit}	No water exposure (dry environment): C_{crit} = 0.5 %; Troughs (the cyclic wet and dry environment): C_{crit} = 0.4 %.
End time of initiation phase	t	Stage 2 onset time: T(2). Stage 6 onset time: T(6).

VII. Example of lifetime calculation of the effect of carbonation – Stage 2

The calculation is made for the combination of the following factors:
- surface position – the horizontal bottom surface;
- characteristics of the element – the surface is not positioned at sides of the span;
- reinforcement – non-stressed reinforcement;
- concrete cover depth – up to 10 mm;
- no surface trough.

The average value of this combination of factors:
T_{mean} = 56 years.
The standard deviation:
$Stdev$ = 28.7 years.
The boundary time:
$T_s(-Q1) = 56 - 0.6475\cdot 28.7 = 37$ years.
Stage 2 onset time:
$t_s(2)$ = 35 years.
The concrete carbonation resistance is calculated using equation 1:
$R_{FC}^{-1} = 5.52\cdot 10^{-11}$ m^5(s·kgCO_2).

VIII. Conclusions

1. The method presented in this paper evaluates the reinforcement corrosion deterioration in 10 stages and allows for systematic identification of the influence of different environmental and structural design factors on the durability of a reinforced concrete bridge.

2. By performing the quantitative analysis of the interaction between the environment and the structural design factors, it is determined that 64.8 % of the bridge surface areas observed showed no signs of damage, while secondary reinforcement defects made up 14 % of the surface area and primary reinforcement defects made up 4 % of the surface area.
3. The proposed method can be used to determine the values of reinforcement corrosion deterioration development parameters (carbonation resistance R_{FC}^{-1} and chloride diffusion coefficient D_{FC}) in order to make forecasts on the service life of bridges with corresponding factor combinations.
4. A factor combination and the stage of damage characterize the actual interaction between the environment and the specific bridge design, which can be similar for a variety of bridges and allows empirical residual lifetime predictions to be made.
5. The method systemizes the information on reinforcement corrosion deterioration stages and the amount, which can be acquired by visual bridge inspection, therefore lessening the subjective interpretation of bridge inspection information.
6. The fact that there are a lot of bridges in Latvia that have received very little maintenance during their service life allows for the more effective use of this method because the deterioration has not been affected by repairs.
7. The proposed method of service life forecasting will help to improve maintenance planning, which in turn will reduce the expense of maintenance, repair and restructuring. The method will help engineers to better understand the nature of bridge deterioration, its significance and possible consequences. The method can also be employed in bridge design to find optimal design solutions that ensure durability.

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