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Validation model for service life prediction of concrete structures

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Abstract
Most bridges in the highways of the Netherlands are designed to last 80 years. In those 80 years only minor damage should be repaired. To determine the repair strategy of these minor damages the so-called Lifetime Extending Maintenance model can be used. This model is a condition model, which has been used for many materials like paint on steel [1]. In this paper we will show an application of this model with which the repair strategy of concrete structures has been validated.

1. Introduction

The ministry of Public Works and Water Management is the principal of about 4000 bridges in the Netherlands [2]. As a principal Public Works likes to know the remaining service lifetime of its structures. During their expected lifetime of 80 years [3] the structures will need repair. At this moment a repair strategy that is based on inspections is used to determine when repair will be done. This repair strategy for concrete bridges in the Netherlands results in repair of bridges every 25 till 35 years. The repair will normally be 0.5 till 1.5% of the area of the structure.

The Lifetime Extending Maintenance Model can simulate repair strategies for newly build structures. It is used to optimise the costs for repair and replacement during lifetime. Important parameters for this model are the rate of deterioration of the materials and the costs to repair the damage. This paper will be focused on how material models and inspection data can improve the results of the Lifetime Extending Maintenance Model.

2. The Lifetime Extending Maintenance Model

2.1 Basic characteristics of the LEM model

The Model is based on a replacement model to which a Lifetime Extending Maintenance model module has been added. A deterioration process of a structure in a Lifetime Extending Maintenance model simulation can usually be subdivided into two parts: (i) an initiation period and (ii) a propagation period. During the initiation period, the lifetime extending measure is fully effective and the structure does not deteriorate at all. During the propagation period, the lifetime-extending measure loses its effectiveness and the deterioration sets in. The "net propagation curve" (Figures 1,2) is defined as the curve describing the condition without lifetime extension as a function of time, starting at the beginning of the propagation period. Lifetime-extending measures can be superposed on this net propagation curve, which results in the overall condition with lifetime extension.

Possible lifetime-extending measures are:

- starting a new initiation period (Figure 1);
- improving the component's condition (Figures 1,2);
- changing the rate of deterioration:
  Repeating: After every lifetime extension the rate of deterioration is the same and equals the rate of deterioration of the net propagation curve at time zero; in other words, after every lifetime extension the propagation curve repeats, as is the case for paint on steel (Figure 1);

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Non-repeating: After a lifetime extension the propagation curve is the same as the net propagation curve at the corresponding condition as is the case for concrete structures (Figure 2).

To determine the moment of action the condition of the material should be described properly. In the figures 1 and 2 two examples of condition description are given. In figure 1 the condition is described in mm, which can be the thickness of a steel plate. In figure 2 the condition is described with a percentage, which can be the undamaged area of a surface. If the repair costs are low compared to the replacement costs the strategy will depend mainly on the changes in condition of the structure in time. This is mostly the case for concrete structures.

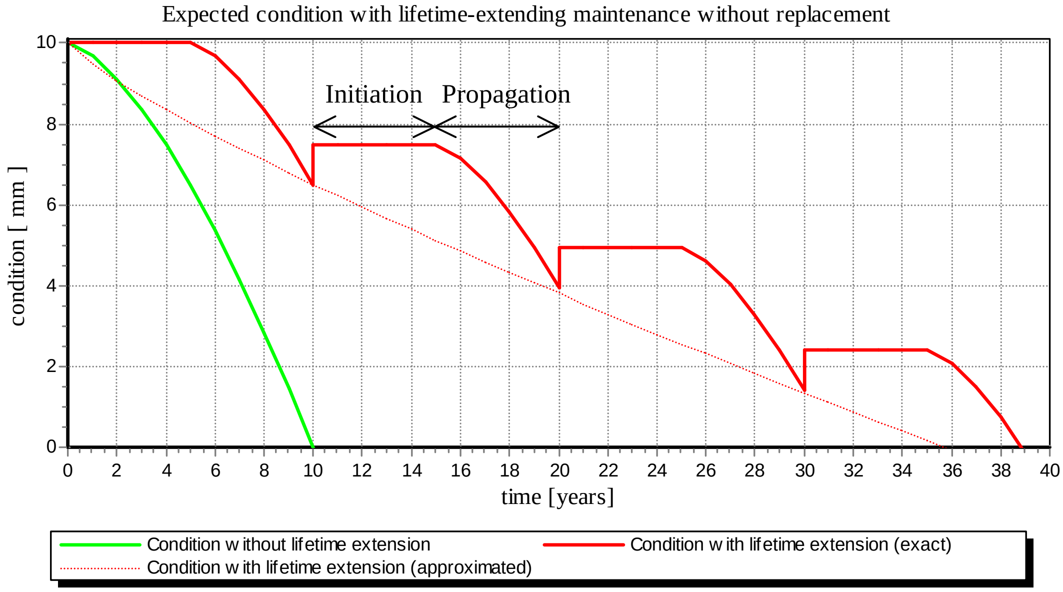

Figure 1. Example of lifetime-extending maintenance with repeating propagation curve.

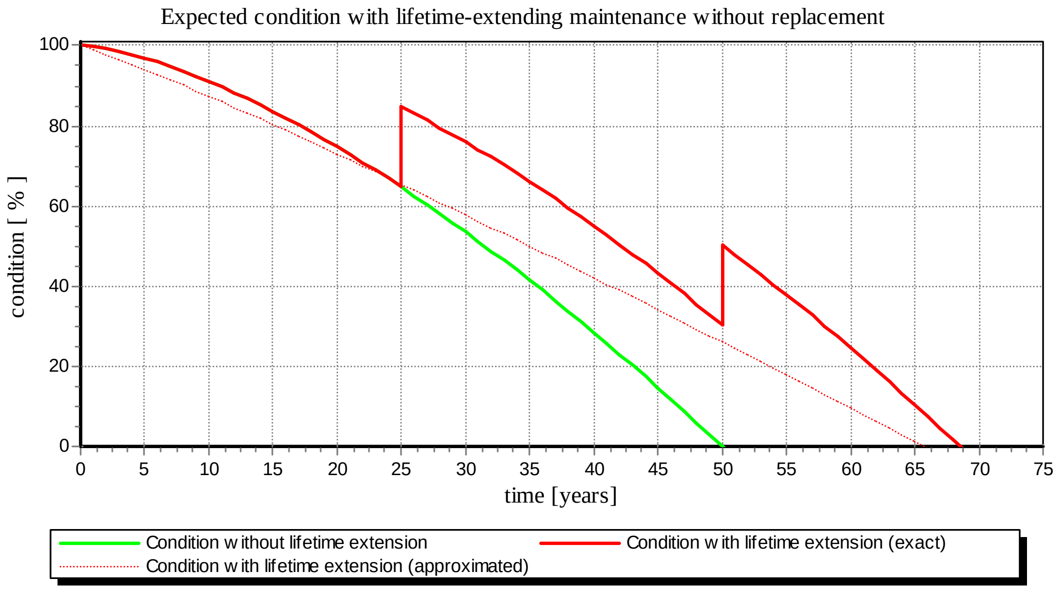

Figure 2. Example of lifetime-extending maintenance with non-repeating propagation curve.

The uncertainty in the rate of deterioration can be specified in terms of the uncertainty distribution. For each combination of the interval of lifetime extension and the interval of preventive replacement, the Lifetime Extending Maintenance model calculates the expected discounted costs over an unbounded horizon. The expected costs are determined by summing the present values of the costs over an unbounded horizon. The future costs are discounted on the basis of a long term discount rate (usually defined as the nominal rate of interest minus the rate of inflation).
According to Van Noortwijk [4], these expected discounted costs over an unbounded horizon can be derived using the discrete renewal theorem. The expected discounted costs over an unbounded horizon are also denoted by the Net Present Value (NPV).

2.2 Simulation parameters
The input of the Lifetime Extending Maintenance model consists of deterioration parameters, lifetime-extension parameters, and cost parameters. The deterioration parameters determine the propagation curve from the time at which the deterioration starts until the time at which the condition equals the failure level (without taking lifetime-extending maintenance into account).
The lifetime extension parameters describe the effect on the net propagation curve after carrying out lifetime extending maintenance, as described above. The four cost parameters that can be distinguished are:

1. cost of investment (building)
2. cost of preventive replacement (replacing before failure)
3. cost of corrective replacement (replacing after failure)
4. cost of lifetime extension.

For each combination of the interval of lifetime extension and the interval of replacement, the Net Present Value is calculated. The output of the Lifetime Extending Maintenance model consists of the optimal preventive lifetime-extension interval and the optimal replacement interval, as well as the expected time to failure and the minimal Net Present Value. Notice that if corrective replacement is optimal, the optimal preventive replacement interval is (theoretically) unbounded.

2.3 Condition model
The condition of the material is described with the following function:

Condition = start condition – damage

Condition function: $y = c - at^b$

Table 1: condition parameters

parameter		in case of concrete
y	condition	% of area that is undamaged
c	start condition	100 %
a	constant	rate of deterioration
b	power constant	

The formulation is not an exact formulation of the condition. This formulation however can be used for many materials. For the purpose in the Lifetime Extending Maintenance model this formulation is accurate enough. The results of the Lifetime Extending Maintenance model depend on the quality of the condition model. Therefore the parameters of the model has been determined with the aid of material models and practical data as will be shown in the following section.

3. Material models

3.1 Diffusion model
The main cause of deterioration of concrete bridges is the use of de-icing salt resulting in chloride induced corrosion of the reinforcement [5]. If the reinforcement is corroded this can result in spalling of

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the concrete. In his research G. Gaal has shown the relation between the risk of corrosion and the spalling observed in practice [6]. These results has been used tot determine the shape of the condition function.

To determine the risk of corrosion of the reinforcement Fick's second law of diffusion has been used:

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x}\left(D(x,t,C)\frac{\partial C}{\partial x} \right)$$

with:
C chloride concentration
D diffusion coefficient
x distance from the surface
t time

The risk of corrosion is based on the assumption that spalling will occur if the chloride content in cement will exceed the critical chloride content. By using the variation coefficients on the input parameters the risk of corrosion is calculated. The result of an example of this calculation is shown in figure 3.

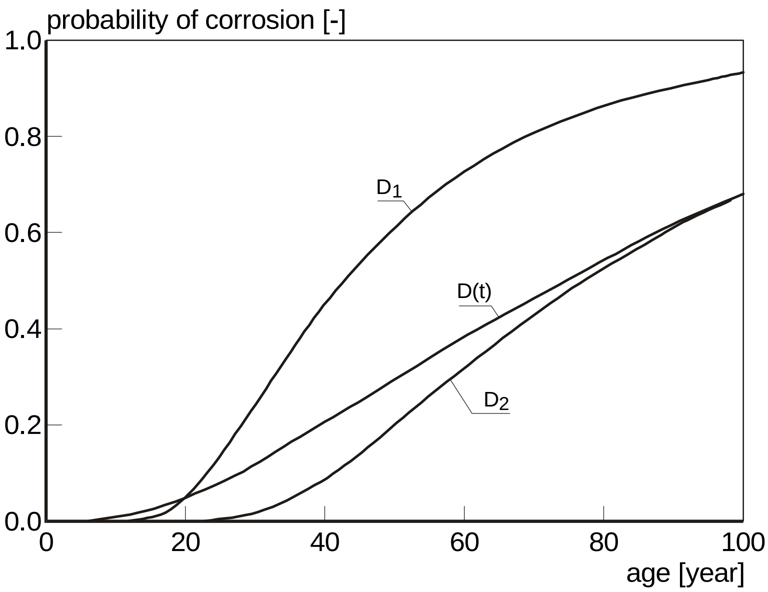

Figure 3 Example of probability of corrosion due to chloride ingress.
D_1 = probability calculated with a constant diffusion coefficient (high)
D_2 = probability calculated with a constant diffusion coefficient (low)
D(t) = probability calculated with a time depending diffusion coefficient

3.2 How to use this figure for the condition model.

The aim of the used model is to determine the shape of the condition function. The assumption used to determine the shape is that if corrosion starts the concrete will show damage. In other words if 1% risk of corrosion is expected 1% of the area the steel will be corroded. This assumption will overestimate the area of the concrete surface with damage (initiation is not equal to spalling and the relationship between corrosion of steel and spalled concrete depends on many factors like cover depth and the density of the reinforcement). The shape of the line representing the deterioration (D(t)), however, seems to be equal to the shape of the line representing the damage in practice [6]. The condition function used cannot describe the whole damage history from 0% damage till 100% damage. The maximum damage observed in practice, however, will not exceed an area of 25%. If we focus on this part of the probability of initiation of corrosion it can be fitted with the condition function. The power factor obtained can be used in the condition model to determine the shape of the function. The value for constant *a* will be determined from observed deterioration (i.e. spalling) in the next section.

With the results of the material model as presented in figure 3 the parameters of the condition model are determined:
Constant a = 0.051
power constant b = 1.6

3.3 Experience from practice (expert judgement)
The Ministry of Public Works and Water Management has a lot of experience with repair of concrete structures. Most of this knowledge comes from the people in practice. Based on their experience it is said that concrete bridges are repaired every 25 till 35 years (accidents, bad construction etc. not taken into account). The repaired area at that moment is about 0.5% till 1.5% of the surface area. With this expert judgement information constant *a* in the condition function is determined:
Constant a= 0.0044
Constant b=1,6 (taken from the risk of corrosion calculation in section 3.2)
Estimated Coefficient of variation of the condition at the time at which the expected condition equals the failure level is 20%.

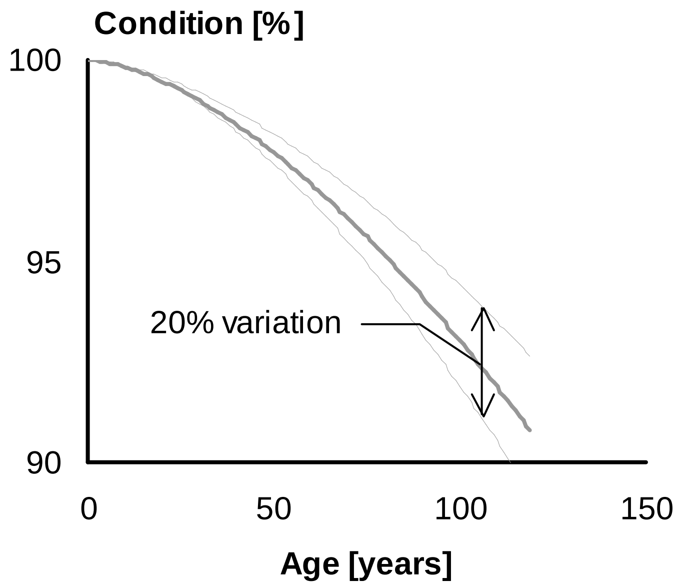

Figure 4 Condition model according to the experience at the Ministry of Public Works. The 20% variation holds for the condition at the time at which the expected condition equals the failure level of 95%.

4. Validation of the models
Both models are based on assumptions that have to be proven in practice. G. Gaal has validated the diffusion model for concrete bridges. Over 100 cores were taken from 16 bridges in the Netherlands to determine chloride profiles. From these profiles the parameters for the chloride diffusion model are derived [7].

The condition model has been validated with inspection data from the renovation of the highway A10 at Amsterdam, the Netherlands. The data was from the topside of the bridge decks. The damaged area was measured to determine the repair required. The bridges had an average age of 29.4 years. The average amount of damage was 0.6% of the examined area as is shown in figure 5.

This data was used in the condition model as follows. The power constant b was taken 1.6 based on the material model in section 3.2. The constant *a* has been altered to obtain a good fit.
Constant a = 0.0026
Constant b = 1.6 (taken from the risk of corrosion calculation in section 3.2)
Estimated coefficient of variation of the condition at the time at which the expected condition equals the failure level is 50%

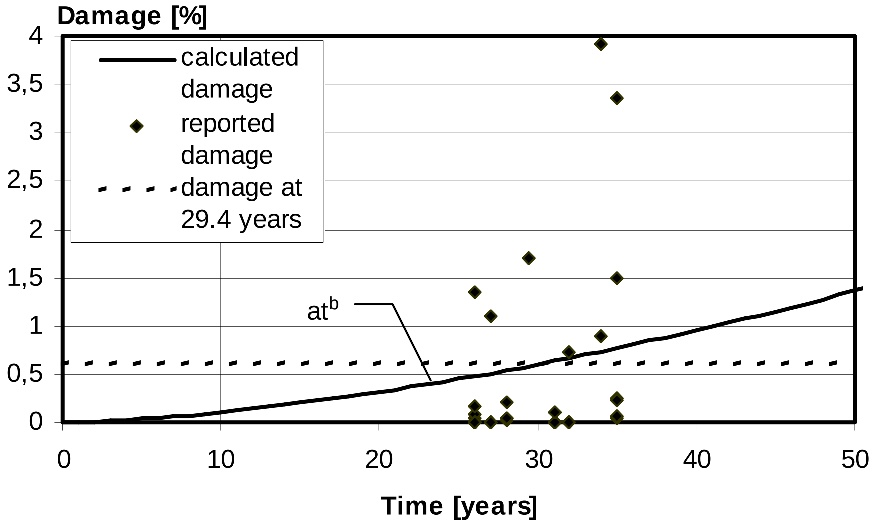

Figure 5 Reported damage at highway A10

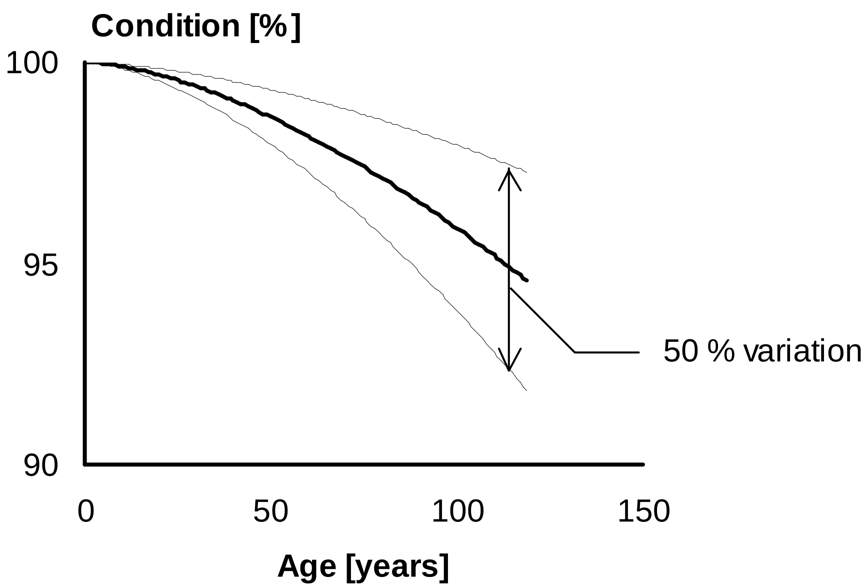

Figure 6 Condition according to data of highway A10

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5. Example of a concrete bridge

In this example an indication of the effect of different condition parameters on the repair strategy is given. The repair strategy of a simple bridge deck has been optimised with the Lifetime Extending Maintenance model. For the optimisation the costs for repair have been seen as relatively low compared to the costs of replacement. Each time repair has been done 1% of the total concrete area has been repaired. The cost parameters for the optimisation are presented in table 2.

In the simulation the effect of the two sets of parameters is shown (table 3). In figure 7 the repair strategy is shown if the original condition parameters from the expert judgement (section 3.3) are used. In figure 8 the repair strategy is shown if the new condition parameters from the highway A10 (section 4) are used. The optimal repair interval shifted from 30 to 45 years. The interval has increased because there was less damage in practice compared to the expected damage.

Table 2: Set of cost parameters

Concrete area of the bridge deck	1000	m2
Costs of replacement	2000	k€
Fixed costs of repair	200	k€
Costs for repair per m2 damage	1000	€/%
Discount rate	1	%

Table 3: Condition parameters

	Expert judgement	Highway A10	
Start condition c	100	100	%
a	0.0044	0.0026	
b	1.6	1.6	
Variation coefficient	20	50	%
accepted condition	95	95	%

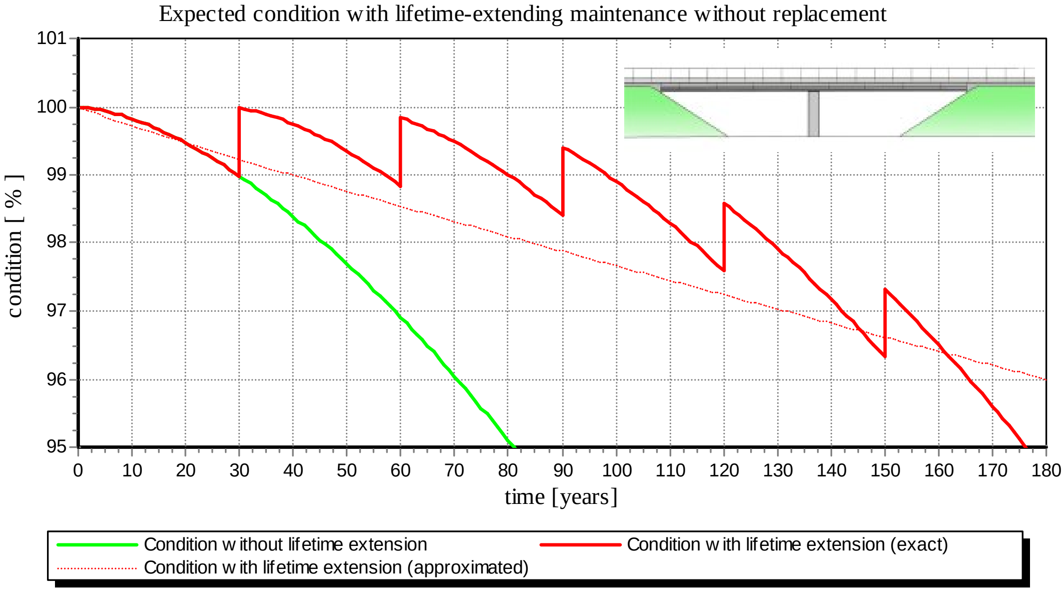

Figure 7 Optimal maintenance interval of 30 years

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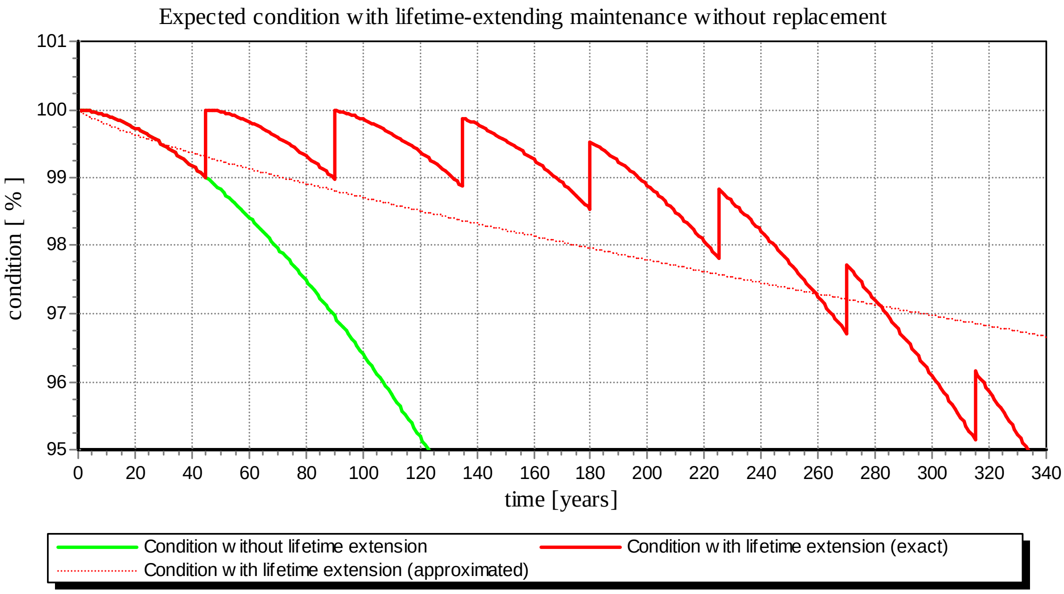

Figure 8 Optimal maintenance interval of 45 years

6. Discussion

The results presented in this paper give an indication of the effect of the deterioration rate of concrete on the repair strategy. The result seem to correspond with the experience in practice. The input parameters used however are based on a small set of data.

The results presented in this paper are based on both models and data from practice. The constants in the condition model should preferably be determined from field data alone. The amount of data present at the moment is not enough to determine both parameters. Therefore a material model was used to determine one of the constants.

If more data becomes available and both parameters can be determined from this data, the use of material models will change. These models can then be used to show the relation between damage observed in practice and possible causes. Before the models can be used for this, they should be improved, mainly by improving the used parameters. The parameters can be improved by collecting more data of chloride induced damage in practice.

An important factor for the repair strategy is the damage that is accepted during lifetime. In this simulation only 5% damage was accepted. If this acceptance level is higher or lower, the repair strategy and replacement strategy can change completely.

The optimal repair strategy presented here is focussed on only one technical aspect of the bridge, without taking into account social and political aspects. These aspects are often dominant for the repair strategy. At this moment repair of the bridge deck takes place when the top layer (mostly asphalt) is renewed.

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7. Conclusions

The use of the lifetime extension model can be a helpful tool to determine optimal repair strategies in practice. Critical for a good optimisation is a representative description of the condition of the structure. Most of the damage in concrete is caused by chloride induced corrosion. Therefore, the basis for the condition model has been the diffusion model for chloride penetration. Combined with experience from practice the condition parameters that are used in the model, were determined. These parameters were validated with data from inspections on highway A10 in the Netherlands. It is shown that data from practice can be used to optimise the repair intervals. Not only for concrete, but also for many other materials used in civil engineering like steel and paints, the maintenance strategy can be optimised by using this type of models.

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