Use of advanced corrosion monitoring for risk based management of concrete structures

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Reinforced concrete is a cost effective material used widely in our infrastructure. The durable combination of steel and concrete provides safety and serviceability. Normally, the physics and chemistry of concrete protects reinforcing steel against corrosion. Over time this protection can be lost due to aggressiveness from the environment, for example chloride ions from seawater and de-icing salts, causing corrosion. Corrosion is the main cause of damage to concrete structures. Due to ageing of the infrastructure, maintenance costs have increased to a major part of the total costs. Proper management should include taking measures for repair and re-install corrosion protection before danger occurs.

For owners of structures corrosion is difficult to handle because there are no objective tools that inform them about the corrosion state. With such information they could take remedial actions well before damage appears and their spending on repairs would be reduced.

Monitoring would allow a more cost effective management of corrosion in concrete. Monitoring systems should be based on embedded sensors for early detection of corrosion, combined with software that translates monitoring signals into the level of risk and the point in time when the structure needs repairs or other interventions.

The paper combines the domains of corrosion in concrete and sensors to monitor its progress with risk and reliability of structures. It gives an example of costs savings due to monitoring and provides underlying statistical data from the field. The ultimate goal is building software tools to design monitoring systems and sensors and to interpret signals in terms of risk of damage and to effectively and economically undertake necessary interventions.

Keywords: Concrete structures, reinforcement corrosion, monitoring, risk evaluation, management

1 Introduction

Reinforced concrete is a very cost effective construction material, used for a large part of the world's physical infrastructure. The durable collaboration between steel and concrete is essential for its safe and serviceable functioning. Normally, the physical and chemical nature of concrete protects the embedded reinforcing steel against corrosion. However, in the course of time, this protection can be reduced or completely lost due to the ingress of aggressive substances from the environment, for example chloride ions from seawater and de-icing salts and carbon dioxide from the atmosphere, resulting in reinforcement corrosion. Corrosion creates expansive corrosion products, which crack and subsequently spall off the concrete cover; eventually corrosion will reduce bar diameters to unsafe values and collapse cannot be excluded.

Corrosion of reinforcement is the main cause of damage to concrete structures. The European infrastructure has reached an age where maintenance costs have increased to such an extent that they constitute the major part of the total costs.

The occurrence of corrosion in concrete structures shows an extremely wide distribution. Some structures will not develop corrosion over a period of 100 years or more, and some already show damage after a decade of service [Gaal 2004]. This wide distribution is due to strong variations in cover depth, concrete quality, environmental aggressiveness, level of routine maintenance and several other factors. This means that it is difficult to evaluate the durability of a particular structure exposed to aggressive conditions *a priori*, without specific information from it. Considering that in Europe probably hundreds of thousands of structures are in aggressive conditions, a statistical approach to condition control related management is required. National (road, railway) authorities and many private stockowners have management systems in place (e.g. for bridges) [Li Ying 2004]. They are based on routine visual inspections of structures which are supposed to signal the appearance of damage. Such an approach thus allows taking countermeasures in the right place, but not necessarily at the right time.

This paper intends to show that the approach based on visual inspection may not be cost-effective and that money can be saved by using more advanced monitoring systems that warn beforehand where and when corrosion will cause a significant risk of damage.

2 Stages in development of corrosion damage

The development of corrosion in concrete over time is generally seen as a multi-stage process as shown in Figure 1 [Bertolini et al. 2004]. In the first period, aggressive substances such as chloride ions or carbon dioxide penetrate the cover and ultimately reach the steel, which causes the onset of corrosion (mark 1), called depassivation or corrosion initiation. In the second stage, actual corrosion takes place (its rate depends on moisture and oxygen availability) and the expansion due to corrosion products being formed builds up tensile stresses in the concrete cover until it cracks (mark 2). This cracking produces the first visible signs of corrosion, although in some cases, rust stains at the concrete surface may show before cracking. In the next stage, expansion due to

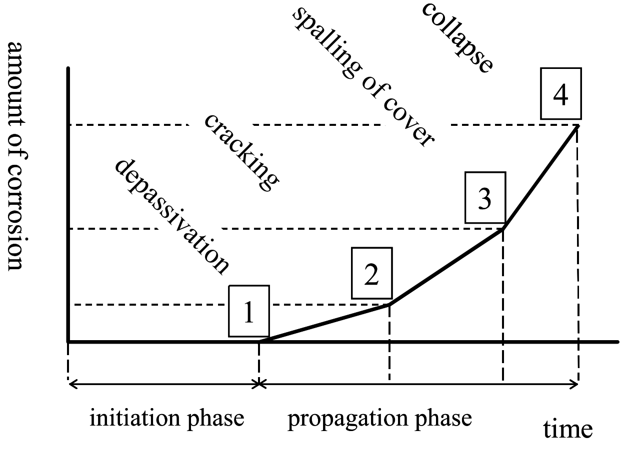

Figure 1: Various stages in the development of reinforcement corrosion in concrete

corrosion proceeds until parts of the concrete cover completely detach and spall off (mark 3), constituting a potential danger for users of the structure or the general public. In the fourth and final stage, reinforcing bar diameter loss becomes so severe as to approach the minimum required for structural stability; eventually, collapse cannot be ruled out (mark 4). The period from $t = 0$ until mark 1 is called the initiation stage. The period from mark 1 until mark 4 is generally called the propagation stage. In civil engineering terms, each of the marks can be seen as a limit state. Service life design methods generally only model the development until mark 1, although attempts are being made to include the next stages 2 and 3 [DuraCrete 2000] and more recently even stage 4.

3 Management strategies for damage control

For management of structures in aggressive environment two basic strategies are available, which might be called popularly "wait & see" and "monitor the invisible". In the forthcoming *fib* New Model Code these strategies will probably be called "reactive" and "pro-active" approaches, respectively. The “wait & see” or "reactive" strategy employs regular visual inspections, e.g. with five year intervals. Visual inspection will not observe anything until a significant amount of damage has developed (stage 2, possibly into stage 3), which causes a high cost of repair in the short term (see below) and potentially the need to decommission the structure from use for a considerable period of time. Monitoring using embedded sensors (as a pro-active strategy) allows following the (invisible) ingress of aggressive substances continuously (in practice on a monthly to annual basis) [Bigaj 2003, Jensen 2002, Klinghoffer 2002, Goltermann 2002]. This would provide advance warning that corrosion initiation may be approaching (before mark 1), such that preventive measures can be taken to delay the onset of corrosion. Such preventive measures are less expensive than full-scale repairs and cause less disruption to the use of the structure. Applying preventive measures will obviously delay subsequent propagation. The effect on the subsequent stages is shown in Figure 2 and the cost consequences are schematically shown in Figure 3; see also the example below.

4 Management of concrete structures for minimal cost

Proper management of structures will aim at preventing corrosion damage or taking measures to repair damage and re-install corrosion protection well before serious danger occurs. The bottom line is that national laws and (international) Standards prescribe the acceptable probability of collapse (mark 4) at a very low level (about 1 in 10,000 or 0.01%). No such clear and strict requirements exist for the earlier stages; in fact each owner can decide about the acceptable probability of reaching e.g. marks 1 or 2. Governmental owners tend to accept a probability of failure for new structures with respect to stage 1 (initiation of corrosion) of the order of 1 to 10% [Siemes et al. 1998, Fluge 2001]. It appears

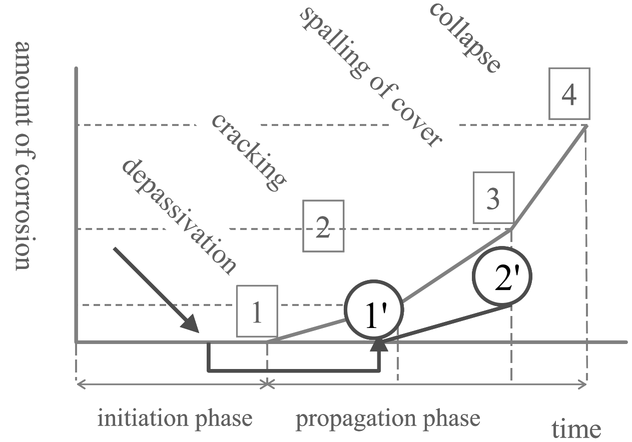

Figure 2: Effect of early warning by a monitoring system and applying preventive measures (diagonal arrow) on the delay of marks 1 and 2

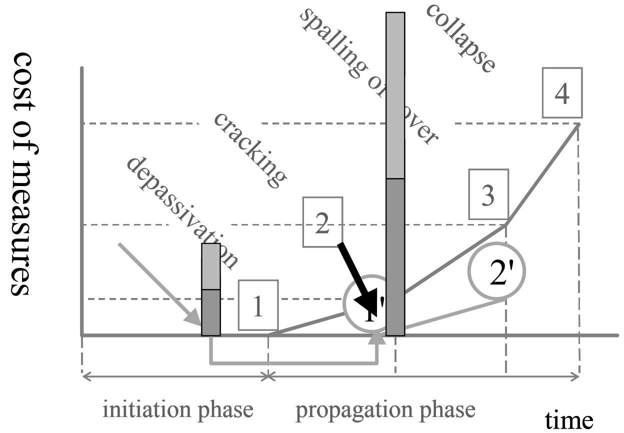

Figure 3: Effect of early warning by a monitoring system on cost of applying preventive measures (left column) or waiting until visual inspection shows that full scale repairs are needed (black arrow, right column); see example case below

rational to take costs into account in decisions about acceptable failure levels. Actually, in view of the uncertainties in the various processes and the large amount of structures owned by stockowners, it may be better to base maintenance decisions on risk. Risk is the cost of an event happening (e.g. repair) multiplied by its probability. For their general policies, many private stockowners take decisions on the basis of risk. Accurately calculating the risk of repair costs requires sufficient statistical data, which are not available at present. Instead, we present an example of the effect on costs of having an "early warning" monitoring system.

5 Example Case

An existing car park of 10,000 m^2 (floor surface area) is aged 10 years. With de-icing salts being brought in by vehicles into the unprotected structure,

- mark 1 in Figure 1 (corrosion initiation) will be reached in 10 years from now (i.e. at age 20)
- mark 2 (cracking) will be reached in 12 years (age 22);
- mark 3 (spalling) is reached in 16 years (age 26);
- and mark 4 (loss of structural safety) will be reached in 25 years (age 35), which is unacceptable by law and Standards.

Various options for intervention are available for preventing/stopping corrosion and/or repair of damage. In general, preventive interventions are cheaper than corrective interventions. However, such cheap interventions can only prevent corrosion from starting, but they cannot stop corrosion that is already ongoing. So, the cost of effective interventions depends on knowing the stage of degradation.

If applied before corrosion has initiated (i.e. before mark 1 is reached), hydrophobic treatment will stop further chloride ingress and prevent corrosion from developing. Therefore marks 1, 2 and beyond will not be reached and/or delayed significantly (Figure 2). Alternatively, if mark 1 has already been reached and mark 2 is approaching, hydrophobic treatment will not be able to stop the development of damage. Therefore, more expensive intervention (some repairs, a dense coating) is needed. After cracking (mark 2) has occurred and spalling (mark 3) is becoming apparent, extensive repairs are necessary and active corrosion must be stopped, e.g. by cathodic protection. The estimated average industry costs of interventions (bottom half of columns in Figure 3) are:

- Stage 1 hydrophobic treatment or simple coating € 25 / m^2
- Stage 2 local repair and high performance coating € 100 / m^2
- Stage 3 extensive repair and cathodic protection € 300 / m^2
- Stage 4 replacement of the structure (rebuilding) € 1000 / m^2.

Additional or indirect costs can be significant and must be taken into account. Indirect costs in this case are the loss of parking revenues during the period for carrying out interventions. Extensive repairs cause a longer period of closure than simple preventive measures. Here these indirect costs are estimated to be equal to the (direct) cost of intervention (top half of columns in Figure 3). The development of costs with time is indicated in Table 1, using the cost levels given above.

The example shows that if the owner knows that mark 1 is soon to be reached, which would be possible if a monitoring system for corrosion (MSC) had been installed, he can take (relatively cheap) preventive measures as illustrated in Figure 3. The cost of installing a MSC is estimated at 250 k€ with 50 k€ additional cost. Waiting until mark 2 has been reached (as would be the case when the owner relies on visual inspection), will cost four times the amount (and 8 times if the indirect cost are also taken into account). The potential saving with MSC indicated in Table 2 may be of the order of a million Euro.

Having installed a MSC in a structure at the age of 10 years following the pro-active strategy, would allow for a monitoring signal to indicate that corrosion initiation (mark 1) is coming up, say in year 15. The decision on whether or not to take preventive measures can be made well in advance. Further monitoring can be used to check the quality of the

Table 1: Cost of interventions for a car park of 10,000 m^2 (floor surface area)

Age (year)	Stage	Intervention	Direct cost	Indirect cost	Sum
20	1 corrosion initiation	Preventive	250 k€	250 k€	500 k€
22	2 cracking	Local repair & coat	1,000 k€	1,000 k€	2,000 k€
26	3 spalling	Extensive repair & Cathodic Protection	3,000 k€	3,000 k€	6,000 k€
35	4 collapse	Replace	10,000 k€	10,000 k€	20,000 k€

preventive measures at minimal cost, since the MSC is already in place. The direct cost of MSC could be as much as 250 k€, and still offer the opportunity to make large financial savings, because it will enable to avoid entering stage 2 on the damage continuum (as opposed to the reactive strategy with visual inspection). After cracking and approaching the spalling stage, costs are likely to be 1000 k€ for repairs, thus a net amount of about 500 k€ is saved in direct costs alone.

It should be noted that this example is a gross simplification. The costs of various actions could vary strongly, depending on the local situation. The effect of discount rate should also be taken into account, as well as the cost of e.g. visual inspection. Experience shows, however, that the bigger picture presented by this example is generally correct. Furthermore, in the last few years the cost of MSC are strongly decreasing, mainly due to digital signal transfer and processing.

6 Statistical distribution of corrosion damage

To illustrate the uncertainties associated with large amounts of structures, some data from a recent PhD study are summarised [Gaal 2004]. Gaal carried out a prediction of corrosion in concrete bridges by probabilistic modeling, which was calibrated using field data for bridges in The Netherlands. He found that:

- the service life of bridges determined by corrosion related damage has a very wide distribution; that is, a relatively large number of structures have a much shorter life than the average structure (large standard deviation)
- the first bridges that show spalling (mark 3 in Figure 1) are as young as 15 years old
- at an age of 40 years, 5% of the bridges have spalling over 1/40 of their surface; 1/40 is the amount that owners see as necessitating repairs

Table 2: Potential cost reduction when using a monitoring system (MSC)

		Direct cost	Indirect cost	Sum
No MSC	Local repair & coat	1,000 k€	1,000 k€	2,000 k€
With MSC	Install MSC	250 k€	50 k€	300 k€
	Preventive intervention	250 k€	250 k€	500 k€
	Sum	500 k€	300 k€	800 k€
Savings with MSC		500 k€	700 k€	1,200 k€

- 50% of the bridges exceed the spalling criterion at an age of 70 years ("average service life")
- the time between initiation of corrosion (mark 1) and spalling (mark 3) can be typically as short as about 5 years.

These generalized observations apply to concrete highway bridges in The Netherlands, where the bridges are relatively young (approaching 40 years age), concrete quality and cover depth are considered to be good and the climate is mild. Gaal also analysed results from the USA Bridge Inventory database that was installed in 1968 (after 45 people were killed in a bridge collapse). It shows that in the US (with supposedly lower concrete quality, older bridges and more aggressive climate), at 40 years age:

- 10% of the bridges are "structurally deficient" (supposedly stage 3, possibly approaching stage 4 in Figure 1)
- 15% of the bridges have already been (heavily) repaired after having been found to be structurally deficient.

Based on the authors' various experiences, over Europe these statistics will be the same as in The Netherlands or worse (older, lower quality concrete, more aggressive environment). No statistical overview is available for car parks. It is thought that car parks develop corrosion earlier than bridges, because until recently their internal climate was not considered aggressive. Experience in the UK with many older car parks and increasingly so in Germany, shows that a rapidly increasing number of these structures develops corrosion and needs repairs. For marine quay walls statistical information is scarce. Harbour quays in Norway seem to have relatively short lives, while in The Netherlands the condition after 20 to 40 years of several cases was good [Polder & De Rooij 2005]. In general the condition of quay walls is probably similar to bridges.

7 Risk based approach to durability and monitoring

The example given above presented a case of 100% probability of corrosion and need of intervention. In practice the probability may be less. At the moment, sufficient statistical information is lacking and a fully risk based decision system for interventions including monitoring is yet to be developed. However, a few observations can be made.

If the probability of corrosion would be 10%, installing monitoring systems that cost 100 k€ each in 10 park houses would already save money if only one of them would actually develop corrosion. In the authors view, a probability of 10% is unrealistically optimistic. Reducing the cost of MSC to that level has become possible by applying state-of-the-art wireless and/or digital technology (saving considerable amounts of cabling) and smart sensors, of which an example was given in [Eri & Pruckner 2006]. The next step is to develop the methodology and probabilistic software for designing MSC (e.g. number of sensors) and for translating their signals into risk levels. Research and Development in these areas are underway [Courage et al. 2004, Goltermann & Klinghoffer 2006].

8 Conclusions

This paper describes an approach that combines knowledge from two domains: corrosion in concrete & monitoring sensors and risk & reliability of structures, in order to improve protection control of structures and save repair costs by monitoring using embedded probes. This integrated approach could be beneficial for owners and managers of (large numbers of) structures in aggressive environments, such as bridges, parking houses and marine harbour quays. The result of research based on such an approach would be software tools 1) to design cost-effective monitoring systems, 2) to develop more effective sensors and 3) to interpret signals from monitoring in terms of risk of damage and necessary repairs. This research should be aimed at developing a risk based framework for monitoring, collecting more and better data from the field and building the software. The recent cost reduction for corrosion monitoring is seen as a strong driving force for this development.

For owners of concrete structures, corrosion of reinforcement is difficult to handle because at present there are no objective, low-cost tools that provide accurate information about the corrosion state, let alone about its development in time. With proper information about the future development of corrosion, owners would be in a position to initiate remedial actions well before the propagation of actual damage. The cost of preventive interventions that can be applied effectively prior to the occurrence of damage is considerably less than the cost of corrective actions needed in a later stage.

For an example thought representative for many structures, it was shown that installing a Monitoring System for corrosion in Concrete (MSC) may save considerable amounts of money and additional costs as compared to the usual strategy of visual inspection.

Monitoring systems based on embedded sensors for early detection of corrosion in concrete combined with software for interpretation in terms of risk and time-to-repair would allow more cost effective management of concrete structures in aggressive environment.

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