Preliminary study of life cycle cost of preventive measures and repair options for corrosion in concrete infrastructure

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Maintenance costs of reinforced concrete infrastructure (bridges, tunnels, harbours, parking structures) are increasing due to aging of structures under aggressive exposure. Corrosion of reinforcement due to chloride ingress is the main problem for existing structures in marine and de-icing salt environments. Corrosion cannot be ruled out completely for new infrastructure, even with today's emphasis on design for long service life (e.g. 100 years), a.o. due to local effects such as leakage of joints; consequently, repairs may be necessary.
This study reports on total life cost calculations for various options to prevent or remediate corrosion damage in an example bridge which is exposed to de-icing salts, locally aggravated by leakage of expansion joints.

Scenarios were developed to predict
- **the occurrence of corrosion damage in the joint areas,**
- **total life cycle cost (LCC) effects of using stainless steel reinforcement, (repeated) hydrophobic treatment and cathodic prevention in the joint areas,**
- **cost effects of conventional concrete repair and cathodic protection in the joint areas, depending on the working life of these corrective measures.**

Summarising the preliminary results, using stainless steel reinforcement and (repeated) hydrophobic treatment of concrete in the endangered areas is surprisingly economic. Furthermore, the working life of conventional repairs and cathodic protection are major

parameters affecting the total life costs. A simple tool was developed for predicting the total life costs depending on working life and costs of various preventive and corrective measures.

Key words: Corrosion, reinforced concrete, prevention, repair, cathodic protection, life cycle cost

1 Introduction

The costs of maintaining reinforced concrete infrastructure (bridges, tunnels, harbours, parking structures) are increasing due to aging of structures, which are being exposed to aggressive environment. Corrosion of reinforcement due to chloride ingress is the main problem for existing structures in marine and de-icing salt environments (Bertolini *et al*. 2013). In The Netherlands 5% of motorway bridges, built predominantly between 1960 and 1980, shows cracking and spalling of the concrete cover due to chloride induced corrosion (Gaal 2004). This corresponds to 10% of the bridges showing corrosion initiation at an age of 40 years (Polder *et al*. 2012). Older structures have been built according to older codes, which may not have provided sufficient protection. Moreover, for new infrastructure corrosion cannot be ruled out completely, even with today's emphasis on design for long service life (typically 100 years), either by composition requirements (Eurocodes) or based on service life modelling and performance testing (fib 2006, CUR 2009, Wegen *et al*. 2012). This may be due to various factors, such as unforeseen aggressive loads, e.g. leakage of joints; or to deviations from the intended concrete quality or cover thickness; or to modelling inadequacies (e.g. for carbonation induced corrosion see (Bertolini *et al*. 2011)). Repair of corrosion damage is possible, but costly, potentially disruptive and not necessarily long lived. A European study has shown that 50% of repairs fail within 10 years (Tilly & Jacobs 2007, Tilly 2011). These results were confirmed by a study in The Netherlands (Visser & Zon 2012). In the worst case, this means that after about ten years the structure must again be repaired, involving more costs; and possibly this will go on until the structure is taken out of service.

Traditionally it has been believed that providing sufficient concrete cover of sufficient quality (e.g., resistance to chloride penetration) is the most economical approach to durability. This may be true in general, but less so in aggressive conditions. Experience suggests that "sufficient" is hard to identify beforehand for all cases, for instance in de-icing salt and marine splash environments. Nowadays, several preventive measures are available: using stainless steel reinforcement, hydrophobic treatment of the concrete surface, cathodic prevention, or admixing inhibitors. Objections against such preventive measures concern the additional costs and lack of experience. Their economic effects on the long term and their strengths and limitations are unclear. Are they worth their extra costs? Are they robust? For example, will the preventive effect disappear over time, e.g. when the system providing it is neglected? Or will preventive effects fail due to environmental influences? This paper reports on a study of the economic effects over a period of 100 years for a (simplified) example bridge, attempting to present realistic scenarios and cost levels for three preventive measures. The base case (without preventive measures) is assumed to develop corrosion damage well before 100 years and the cost of four repair and protection scenarios are predicted. Initial costs and maintenance costs have been accumulated and expressed as present value; the result is called life cycle cost. The cost of demolition is not taken into account. The case study is based on the second authors' MSc project report (Pan 2012).

2 Example case

This study is based on a schematised simple rectangular reinforced concrete bridge deck of 28 m long, 8 m wide and 1 m thick. It is designed for 100 year service life by using 50 mm cover depth and a concrete composition (based on Portland cement) with a chloride penetration resistance specified for de-icing salt environment. Using the Dutch CUR Guideline 1 (Wegen *et al*. 2012), a chloride migration coefficient of $15*10^{-12}$ m^2/s is specified for 50 mm cover and de-icing salt environment XD3, a.o. characterised by a chloride surface content of 1.5% of total chloride ion by cement mass. Under those conditions, corrosion initiation will not occur before an age of about 100 years. However, in practice, expansion joints may leak after some time, increasing the chloride load to levels corresponding to XS3, marine splash zone, quantified as 3.0% of chloride. With such an increased load, chloride penetration will be faster and corrosion initiation will occur earlier; in this case after about 30 years. Taking into account a few years before cracking and spalling occur (which must be noticed during an inspection before repair measures are considered), the time until corrosion damage is found to be 33 years. It should be noted that not the complete deck will suffer corrosion; due to the local nature of chloride exposure to joint leakage, only the vertical faces (8 m wide by 1 m high) and the horizontal first meter on the underside of the deck (also 8 m wide by 1 m long) will develop corrosion. These parts are further called joint areas, comprising c. 6% of the total bridge deck surface area. The total cost of the deck is assumed to be 118,000 Euro (118 kEuro), consisting of about 70% labour and 30% materials cost, including 20 kEuro for ordinary steel reinforcement. The reinforcement consists of a mesh of 16 mm diameter at 100 mm centres. A sketch of the bridge is provided in Figure 1. As a side note, the example is loosely based on a real case of a bridge with corrosion damage in the joint areas, to which CP was applied in the 1990s (Polder 1998). The total life cycle cost (LCC) was calculated by adding present values of costs for repair (in specific years) and regular maintenance if required (every year) until year 100 to the investment cost for the bridge deck (in year 1). The rate of interest is set at 2% per year.

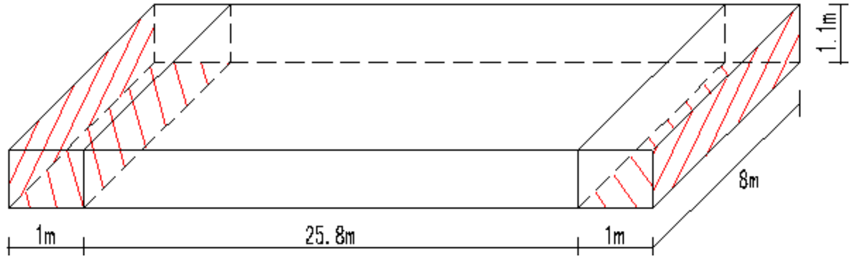

Figure 1. Sketch of the example bridge deck with zones indicated where corrosion and damage will develop due to leakage of joints, called joint areas (hatched)

3 Preventive measures

The various preventive measures studied are briefly described, including their expected price level, obtained from various suppliers. Their effects will be addressed with the discussion of the overall results.

Stainless steel reinforcement, generally based on austenitic stainless steel (chromium-nickel alloys), has a long history but is still not used widely, mainly due to its high price, which is roughly about six times the price of ordinary rebar. Mechanical properties are equivalent or better than ordinary rebar and bending, handling and welding processes are similar (Concrete Society 1998, Nurnberger 1996). Coupling with ordinary steel has been shown to be no problem (COST 521 2003). The critical chloride threshold for corrosion initiation is very high, possibly 5% chloride by mass of cement (Bertolini *et al*. 2013). Consequently, corrosion will not initiate under normal service conditions. Thus, if stainless steel is used in

the joint areas, the bridge will not develop corrosion in 100 years and well beyond. The cost of using stainless steel for 6% of the rebar will be 6000 Euro, which is 5000 Euro increase compared to using ordinary steel for the total bridge.
Hydrophobic treatment involves applying a liquid containing silanes or siloxanes to a concrete surface, which polymerise to silicone that makes the concrete surface water repellent. Consequently, chlorides dissolved in melting water cannot be absorbed. Research has shown the beneficial effects (Polder *et al*. 2001), including slowing down chloride penetration substantially (by 80 to 90%). The Netherlands Ministry of Transport and The Environment has applied hydrophobic treatment to bridge deck top surfaces since the mid 1990's. The Ministry's most recent Guideline for Design of Civil Engineering works also includes hydrophobic treatment of the joint areas of new bridges (ROK 2012). There is some concern about the durability. UV radiation may break down the silicones and reduce the effectiveness of the water repellence in the course of time. Recent studies suggest this may take considerably more than ten years (Christodoulou *et al*. 2013a; Rodum & Lindland 2012, Schueremans *et al*. 2007). To be on the safe side, in this study we assumed that the hydrophobic treatment was repeated every ten years. The price is low; in the construction phase this treatment can be carried out for 25 Euros per square meter (800 Euro total for the joint areas of the example bridge); in the service phase the cost of access increases this figure to 50 Euro/m² (1600 Euro per repeated treatment).

Cathodic prevention (CPre) has been pioneered in Italy in the late 1980s and shown to be effective. Principles and effects have been explained by Pedeferri (1996). The method consists of mounting an electrode onto or into the concrete, called the anode, which is connected to the positive terminal of a low voltage power source. The steel is connected to the negative terminal, causing a current to flow that polarises the steel into the negative direction. This polarisation prevents corrosion; in fact, the critical chloride threshold increases up to possibly 3-5% (Bertolini *et al*. 2009). It should be noted that the current to prevent corrosion is much lower (by a factor of ten) than the current needed to stop active corrosion (as in CP, see below). As an "active" method, CPre needs to be checked regularly, typically twice a year, by testing polarisation. CPre has been covered by a European Standard since 2000 (EN 12696). Installing CPre in a new structure is relatively cheap, as access is simple and less anode material is needed than for CP due to lower current demand. Input figures used are: the cost of CPre is 100 Euro/m² and the cost of checking is 1000 Euro per year. Provided that the checks are done, CPre may be assumed to have a very long life. Here it is assumed that no corrosion will develop in the areas with CPre during the entire life of 100 years.

4 Repair and protection

The repair and protection methods studied are briefly described here, including their expected price level for the base case. Their effects and limitations will be addressed with the discussion of the overall results. No additional cost is taken into account, e.g. for traffic control, which may be significant for repair works on (motorway) bridges in general, but possibly not so much for repairs in the joint areas, which mainly affect only the abutments.

Conventional concrete repair involves breaking out chloride-contaminated concrete, cleaning the steel from corrosion products and chloride ions, applying a cementitious chloride-free repair mortar and curing it. For projects like the bridge this is usually done by manual methods, which presents difficulties for obtaining good quality execution, exaggerated by market pressures. In many cases, chlorides are left in the concrete or at the steel surface, causing corrosion to reappear shortly. This is one of the factors why conventional repairs have an average time to failure of ten years, as mentioned above (Tilly & Jacobs 2007). The cost of conventional repair is estimated at 1000 Euro/m², and its working life at ten years.

At least theoretically it should be possible to repair for much longer times, for example 25 years. Such a LongLifeRepair should involve deep removal of contaminated concrete, assisted by testing for chloride remaining in the concrete; thorough cleaning (and subsequent testing for remaining chloride) of rebars; applying fail-safe repair material (e.g. containing corrosion inhibitor), and applying a durable surface protection for example by hydrophobic treatment. So far, this kind of LongLifeRepair is just hypothetical. Another option for prolonged repair life may be installing sacrificial (zinc) anodes. They are intended to protect areas within and just outside the repair spots against the reappearance of corrosion (Page & Sergi 2000). This technique is not taken into account here. In any case, a special repair with longer life can be expected to involve higher cost than normal repair. For the base case the price is set at 1500 Euro/m² and the working life at 25 years.

Cathodic protection (CP) involves installing an anode on the concrete surface or in the cross section. A low voltage is applied between the anode and the reinforcement and the resulting current, typically 2 – 20 mA/m², will suppress corrosion reactions. Cracked and spalled areas need to be repaired, but no additional breaking out of chloride contaminated concrete is needed, nor steel cleaning. Due to CP those repairs will not suffer from recurring corrosion. Anodes can be of different materials and shapes. Conductive coatings have been used successfully since the 1990s. Their documented working life can be as long as 20 years (Polder *et al*. 2014). Activated titanium mesh or strips in cementitious overlays (sprayed concrete, grout) have a track record that goes back to the 1980s. A working life of well over 20 years has been documented for many cases. A properly installed titanium CP system can probably last some 50 years. For more in-field experience of various types of CP systems on bridge substructures, see (Christodoulou *et al*. 2013b). All CP systems need to be checked by electrical measurements, preferably twice a year with at least one site visit for visual inspection. The relevant European Standard has been recently updated (EN-ISO 12969 2012). The following input data are used. A coating system (with a moderate amount of concrete repair) may cost 300 Euro/m² and will have a life of 20 years. A titanium system will cost 1000 Euro/m² and have a life of 50 year. For the base case, CP systems will cost 2000 Euro/year for checking.

5 Results and discussion

Using the base case input, the resulting costs over 100 year are shown in Figure 2 for the scenarios:

1. Bridge with conventional repair
2. Bridge with “LongLifeRepair”
3. Bridge with CP of 20 years of working life
4. Bridge with CP of 50 years of working life
5. Bridge with stainless steel as preventive measure
6. Bridge with repeated hydrophobic treatment as preventive measure
7. Bridge with CPre as preventive measure

It is clear from Figure 2 that the base case for conventional repair is the most expensive (189 kEuro). Preventive measures, either installing stainless steel rebar or (repeated) hydrophobic treatment are by far the most economical options (both 124 kEuro). With the input used, CPre is third in total life cost (164 kEuro), nearly as expensive as any of the repair/protection options. The cheapest of the repair/protection options is “LongLifeRepair” with 168 kEuro. The base case CP cost for 20 (denoted CP20) or 50

(CP50) years working life are 176 and 180 kEuro, respectively. The various options are discussed briefly.

The base repair case requires seven repair interventions; the pure repair costs over the total life are 71 kEuro. The LongLifeRepair scenario requires three repair cycles. Interestingly, if LongLifeRepair (with 25 year working life) would cost as much as 2000 Euro/m², its total life cost of 185 kEuro is still lower than for conventional repair. Apparently spending significantly more money on a repair can be economically beneficial as long as a longer repair life is obtained. With both types of repair, regular inspections should be carried out to check if the repair is still working. The costs for such inspections have not been taken into account here.

The total life cost of the CP options is strongly influenced by the cost of half-yearly checks. An alternative scenario was calculated with a data logging system and remote control installed, costing 4000 Euro, and 50% lower annual cost (one site visit per year instead of two). The total life cost with CP20+remote would be 163 kEuro; for CP50+remote it would also be 163 kEuro. Consequently, they would (both) become the cheapest of the

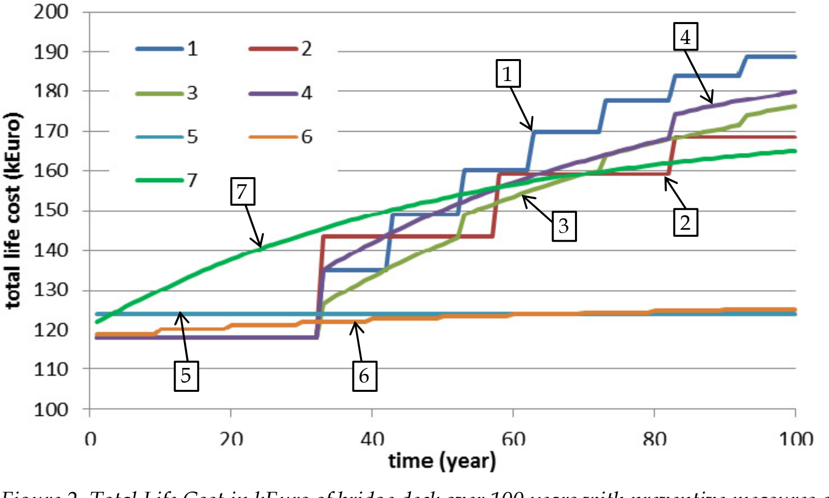

Figure 2. Total Life Cost in kEuro of bridge deck over 100 years with preventive measures or repairs in the joint areas; base case; legend: 1. Bridge with conventional repair, 2. Bridge with "LongLifeRepair", 3. Bridge with CP of 20 years of working life, 4. Bridge with CP of 50 years of working life, 5. Bridge with stainless steel as preventive measure, 6. Bridge with repeated hydrophobic treatment as preventive measure, 7. Bridge with CPre as preventive measure

remediation options! Reducing testing intervals appears possible for CP systems older than 6 years based on field data (Christodoulou *et al*. 2013b). Both the long and successful track record and the relatively low cost make CP an attractive option for bridges with corrosion damage.

As mentioned, CPre is relatively expensive (164 kEuro). Installing remote control can only reduce annual cost if site visits are carried out once every few years. Assuming 4000 Euro for remote control and 500 Euro/year cost for testing, the total would be 147 kEuro. In that case, CPre would be cheaper than each of the repair/protection options; but still more expensive than hydrophobic treatment and stainless steel (124 kEuro each). CPre has the advantage of having "built in" corrosion monitoring. The preventive effect also applies to prestressing steel that may be present in a real bridge deck end beam, at least for about one to two meters away from the joint (Pedeferri 1996, Polder *et al*. 2009).

Hydrophobic treatment is economic, can be simply applied and does not involve monitoring or advanced technology. The preventive action will also positively affect the durability of the prestressing in the end beam. Even if it would not be repeated every ten years, it will probably still be somewhat effective for a long time. However, in order to rely on its preventive effect for 100 years, we believe that the treatment should be repeated once in a while.

Using stainless steel reinforcement is found to be a quite economic option. Even if it were twelve times as expensive as carbon steel, the total life cost (130 kEuro) would be much lower than for any other option except hydrophobic treatment. It is a robust solution, but only for the area where it is used. It does not directly protect prestressing steel in the same area, but it helps keeping the concrete cover intact, which is an important "line of defence" for the prestressing system.

The LCC of these alternative scenarios are shown in Figure 3 for:

1. Bridge with conventional repair (as in Figure 2)
2. Bridge with "LongLifeRepair" costing as much as 2000 Euro/m^2,
3. Bridge with CP of 20 years of working life, optimised by remote control
4. Bridge with CP of 50 years of working life, optimised by remote control
5. Bridge with stainless steel as preventive measure as in Figure 2
6. Bridge with repeated hydrophobic treatment as preventive measure as in Figure 2
7. Bridge with CPre as preventive measure, optimised by remote control.

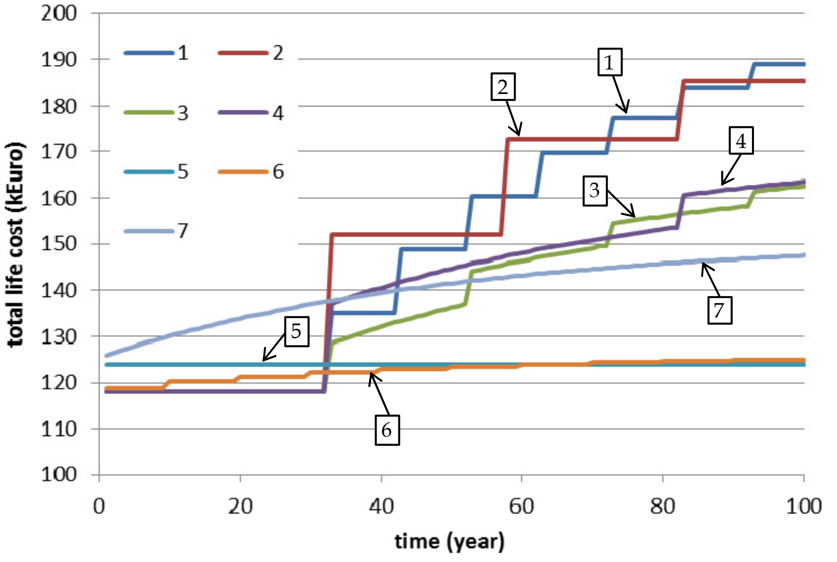

Figure 3. Total Life Cost in kEuro of bridge deck over 100 years with preventive measures or repairs in the joint areas; CP and CPre with remote control and LongLifeRepair for the double price of conventional repair; legend: 1. Bridge with conventional repair (as in Figure 2), 2. Bridge with "LongLifeRepair" costing as much as 2000 Euro/m², 3. Bridge with CP of 20 years of working life, optimised by remote control, 4. Bridge with CP of 50 years of working life, optimised by remote control, 5. Bridge with stainless steel as preventive measure as in Figure 2, 6. Bridge with repeated hydrophobic treatment as preventive measure as in Figure 2, 7. Bridge with CPre as preventive measure, optimised by remote control.

As a final remark: we have used a rate of interest of 2%, which may be realistic at present. However, higher levels may apply over longer periods. A higher rate of interest would decrease the differences between the different scenarios. However, their ranking would not change or only marginally.

6 Conclusions

The total life cycle cost of a bridge deck exposed to de-icing salts was studied for various options for prevention and remediation against reinforcement corrosion in the end beams. It was assumed that corrosion would start at an age of 30 years (due to underestimating the chloride load at leaking joints). Data for both the cost and the working life of various methods of corrosion prevention and remediation were obtained from experience. The initial cost of the (highly simplified) bridge deck was 118,000 Euro. The total life costs of the options applied in the joint areas were in increasing order (in kEuro):

1/2. Stainless steel reinforcement and hydrophobic treatment of concrete (124)
3. Cathodic prevention, provided that a low frequency of testing is applied (147)
4/5. Cathodic protection, either using a conductive coating or titanium mesh in shotcrete, provided remote control were used to limit site visits (163).
6. Repair by a hypothetical method called LongLifeRepair with 25 years working life (e.g. due to addition of some anti-corrosion agent, like hydrophobic treatment or inhibitor); with an assumed price level of 50% more than conventional repair (168)
7. Conventional repair, having 10 years working life as observed in practice (189).

It should be noted that the costs of options were estimated; they may vary strongly depending on local market situations.

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