COST EFFECTIVENESS AND APPLICATION OF ONLINE-MONITORING IN REINFORCED CONCRETE STRUCTURES

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ABSTRACT

The annual costs for the maintenance of the Swiss national road networks amount to SFr. 560-640 millions. Due to the limited means and the large number of engineering structures at the critical age between 30 and 45 years cost-effective solutions for the monitoring and the maintenance of these structures have to be found. In this paper the life cycle costs of an engineering structure using a sensor network (online-monitoring system) were investigated. These costs were compared to the costs of classical inspection techniques.

LIFE CYCLE COSTS OF CONCRETE STRUCTURES

The Life-cycle costs of a structure comprise the following components:

$$C_{TOTAL} = C_{CONSTR} + C_{MAINT} + C_{INSP} + C_{REP} + C_F$$

C_{TOTAL}	=	Total Life-Cycle Costs
C_{CONSTR}	=	Construction Costs
C_{MAINT}	=	Maintenance Costs
C_{INSP}	=	Inspection Costs
C_{REP}	=	Repair Costs
C_F	=	Costs of a possible Failure

In the case of a comparison of the life-cycle costs of a structure with or without Online-Monitoring, there has to be differentiated the costs that change by using different inspection technologies. By taking a closer look at the cost units, there are only three that are affected by different inspection strategies. These are the inspection costs, the costs for repairs and the costs for a possible failure. The construction costs and the maintenance costs are not of interest when comparing Online-Monitoring to classical Inspection. The inspection costs are theoretically captured by the following equation (Mori/Ellingwood 1994):

$$C_{ins} = \alpha_{ins}(1-\eta_{min})^{20}$$

C_{ins}	=	Costs of each Inspection
α_{ins}	=	Costs of an Inspection that detects every damage
η_{min}	=	Minimal damage that has to be detected (equals $0.07*C_{CONSTR}$)

The repair costs (C_{rep}) can be calculated too:

$$C_{rep} = \propto_{rep} \left(\frac{M_{r,a} - M_{r,b}}{M_{r,0}}\right)^{\gamma}$$

α_{rep}	=	Costs for replacing the whole structure = C_{CONS}
$M_{r,a}$	=	actual state of structure after repair
$M_{r,b}$	=	actual state of structure before repair
$M_{r,0}$	=	actual state at beginning of life cycle
γ	=	model parameter (est. 0.5)

QUANTIFYING THE COSTS OF A CLASSICAL INSPECTION

The formula of the inspection costs gives a good guess of the minimum damage that can be detected by applying visual inspection techniques. To be able to make a quantification of the costs, the authors have decided to consider a model of a bridge with the following specifications: length = 117m, width = 25m. This bridge corresponds to an average bridge in Swiss national roads. After modeling the bridge, the average construction costs could be estimated ($2925m^2$*SFr. 2200.- = SFr. 6'435'000). Also the inspection costs are available (average inspection time for a bridge = 4h = SFr. 720.-). After adding the costs for extra inspections, the average costs for inspection result to SFr. 1193.-. Applied to the equation of the inspection costs, the minimum detectable damage rate for visual inspections is 25%. Normally visual bridge inspections are performed every 5 years in Switzerland.

In a next step, the costs of a repair have to be estimated. Due to the high damage rate that can be detected by visual inspection technologies, the average repair costs can be estimated to about SFr. 1500.-/m^2 (local repair of the concrete and partly replacement of the reinforcement). For the model bridge, the costs have been calculated as follows: 0.25*$2925m^2$*SFr. 1500. - = SFr. 1.096'875.-. After having determined the costs of a detected damage, the point of time had to be estimated at which this damage could occur. The authors made the assumption that a damage rate of 25% occurs 50 years after the completion of the bridge.

QUANTIFYING THE COSTS OF AN ONLINE-MONITORED STRUCTURE

While the costs of a classical inspection are delivered by the Swiss road department, the costs of an online-monitored structure were estimated by the authors. The costs of an online-monitoring can be divided into the costs for installing the system and the costs for operating the system.

The costs for installing the system are determined by two main factors:

- How many sensors are installed?
- Is the system installed into a new or existing structure?

The authors decided to install 44 sensors into the bridge deck and 3 sensors into the columns of the bridge. The implementation of 47 sensors results in costs of SFr. 350'000.- for an existing bridge and SFr. 100'000.- for a new bridge. The costs for operating the system have been calculated to SFr. 2000.- per year.

After calculating the costs for the inspection with the online-monitoring system, the damage detection rate had to be quantified. For this calculation a stochastic equation has been used. The bridge deck has been divided into small squares (each square defines the minimum corroding area). Then the sensors were assigned to these squares. The following equation was used to calculate the damage detection rate:

$$d(\eta) = 1 - \left(\frac{(A - S)!\,(A - A * \eta_{KORR})!}{(A - S - A * \eta_{KORR})!\,(A)!} \right)$$

d(η)	=	Probability of damage detection
A	=	Total squares in the bridge deck
S	=	N° of Sensors
η_{KORR}	=	Corrosion rate (%)

In fig. 1 the probability of damage detection has been calculated for different damage rates.

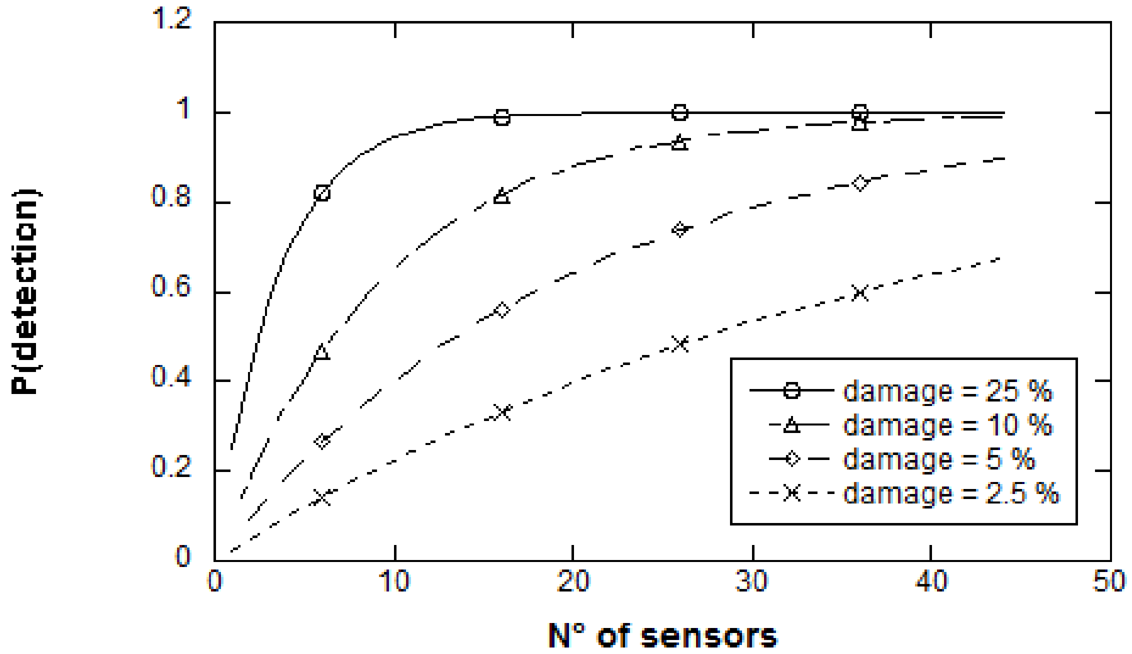

Fig. 1 Probability of detection at a certain damage level

It could be shown, that by use of 44 Sensors in the bridge deck, the damage detection rate with a damage rate of 5% is about 90%. Using this result, the authors decided that a damage rate of 5% can be detected and repaired. This assumption is on the safe side because of the following facts:

Normally the rebar is at a depth of 5-7cm. The Sensor measures corrosion over a depth of 2-7cm. The sensor already measures the start of corrosion before the rebar starts corroding. Assuming that the concrete has no weak spots where the salts and water can get directly to the rebar, the corrosion never gets to the rebar.

Further it was assumed that a damage of 5% results in repair costs for a bridge deck of about SFr. 50’000.-. This sum is much smaller because the bridge deck needs no re-profiling. After the calculation of the repair costs, the occurrences of the damage had to be determined. The authors decided that if a damage rate of 25% results after 50 years, a damage rate of 5% results after 25 years.

COMPARISON OF THE DIFFERENT INSPECTION TECHNIQUES

The main challenge in comparing the two inspection techniques (visual inspection and online-monitoring with a sensor network) is to create an accurate deterioration scenario for the structure. The deterioration of a structure depends on the exposure conditions and the quality of the building materials. Different scenarios would have to be simulated and a more dimensional deterioration matrix would have to be built. The authors just calculated one scenario. This scenario looks as in table 1 described:

Table 1: Inspection and damage scenarios for different inspection strategies

Year	Bridge with Classical inspection	Online-Monitoring
0	No inspection, no damage detection	Install of the Monitoring-System
5	Inspection, no damage detection	Bulletin, no damage detection
10	Inspection, no damage detection	Bulletin, no damage detection
15	Inspection, no damage detection	Bulletin, no damage detection
20	Inspection, no damage detection	Bulletin, no damage detection
25	Inspection, no damage detection	Bulletin, damage detection at a damage rate of 5%. Repair of the damage and modernization of the Monitoring-System
30	Inspection, no damage detection	Bulletin, no damage detection
35	Inspection, no damage detection	Bulletin, no damage detection
40	Inspection, no damage detection	Bulletin, no damage detection
45	Inspection, no damage detection	Bulletin, no damage detection
50	Inspection, damage detection at a damage rate of 25%, Special inspections and repair of the damage	Bulletin, damage detection at a damage rate of 5%. Repair of the damage and modernization of the Monitoring-System
55	Inspection, no damage detection	Bulletin, no damage detection
60	Inspection, no damage detection	Bulletin, no damage detection
65	Inspection, no damage detection	Bulletin, no damage detection
70	Inspection, no damage detection	Bulletin, no damage detection
75	Inspection, no damage detection	Bulletin, damage detection at a damage rate of 5%. Repair of the damage and modernization of the Monitoring-System
80	Inspection, no damage detection	Bulletin, no damage detection
85	Inspection, no damage detection	Bulletin, no damage detection
90	Inspection, no damage detection	Bulletin, no damage detection
95	Inspection, no damage detection	Bulletin, no damage detection
100	Replacement of the structure	Replacement of the structure

All the costs that occur are already defined in the paragraphs above. Only the prize of the renewal of the monitoring system has not been calculated. The authors assume that a renewal only has an impact on the electronics but not on the sensors itself. An amount of SFr. 50’000.- should be an accurate estimation. Now the total costs can be calculated (table 2):

Table 2: Cost of the different inspection and repair strategies

Year	Bridge with classical Inspection	Online-Monitoring
0	0	100’000
5	1’173	2’000
10	1’173	2’000
15	1’173	2’000
20	1’173	2’000
25	1’173	102’000
30	1’173	2’000
35	1’173	2’000
40	1’173	2’000
45	1’173	2’000
50	1’001’173	102’000
55	1’173	2’000
60	1’173	2’000
65	1’173	2’000
70	1’173	2’000
75	1’173	102’000
80	1’173	2’000
85	1’173	2’000
90	1’173	2’000
95	1’173	2’000
100	0	0
Total:	1’022’287	440’000

In the case of an online-monitoring system the accuracy of the damage detection due to the corrosion of the reinforcement depending on the total surface area, the number of sensors and the corroding area was identified. The accuracy of damage detection was calculated by a stochastic equation (Fig. 1). Compared to the early damage detection of the sensor network, a visual inspection has the same probability of detection at a damage rate of 25 %. In a next step the costs of a repair work of the bridge model was calculated, assuming that a damage is repaired after its detection. Using a sensor network cost savings up to 30 % result due to an early detection of the damage (Fig. 2).

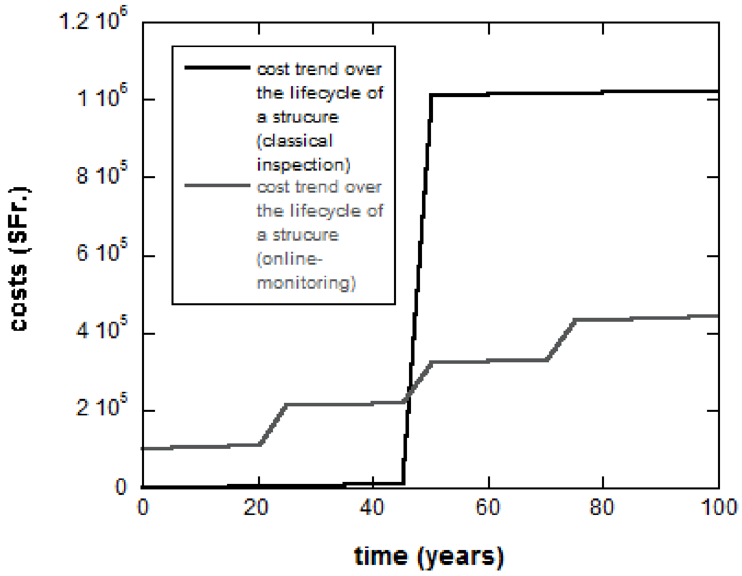

Fig. 2 Cost trend for the Lifecycle of a structure with or without using Online-Monitoring

PRACTICAL APPLICATION: ONLINE-MONITORING OF A TUNNEL SLAB

To verify the theoretical results, the benefit of an online-monitoring system for the repair of a damaged structure is shown for a corroding tunnel slab in a large Swiss road-tunnel.

In the portal zone of a large Swiss road tunnel high chloride concentrations and corroding reinforcement was found during several inspections. To lower the corrosion rate a hydrophobic impregnation was applied and four test fields were instrumented with sensors to measure the corrosion current (macrocell current) and to control the effectiveness of the impregnation (lower the water content in the concrete).

During one night two test fields in the northern part of the tunnel were sprinkled with water. Fig. 3 shows the cumulative material loss of the corroding reinforcement steel inside four test fields after half a year. The hydrophobic impregnation reduced the corrosion by a factor of 4 within the sprinkled test fields. But also the test fields without sprinkling showed a clear decrease of the corrosion rate due to the impregnation of the concrete surface.

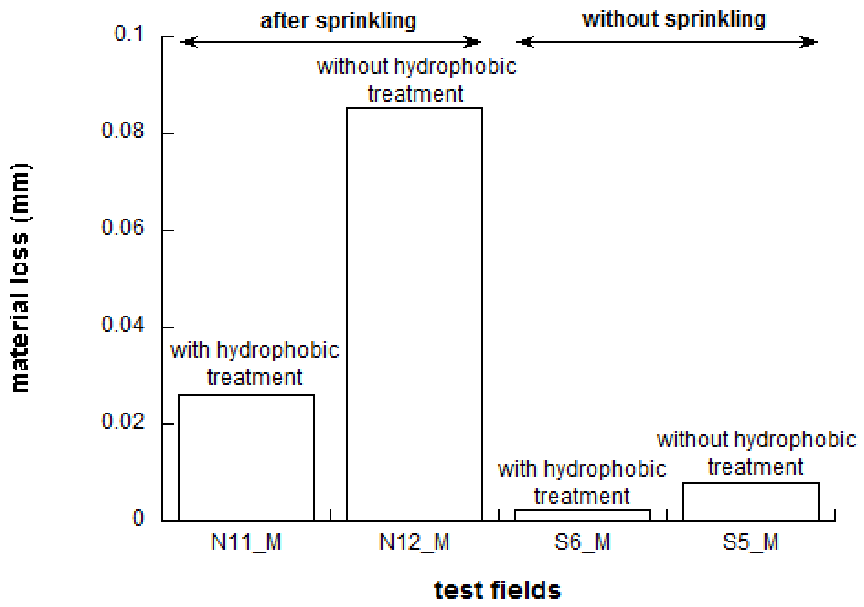

Fig. 3 Effectiveness of a hydrophobic treatment on the corrosion in a tunnel slab

CONCLUSIONS

Using an online-monitoring system can lead to a clear reduction of the running costs over the lifetime of a structure:

- corrosion detection: classical inspection detects corrosion if already 25 % of the structure is damaged. A suitable sensor network detects corrosion if 5 % of the structure is damaged
- The use of an online-monitoring system leads to a distinctive reduction of life-cycle costs of reinforced concrete structures:

- due to an early detection of failures the cost for measures to preserve the durability of the structure can clearly be lowered
- more detailed condition assessment and more adequate measures

- An online-monitoring system with sensors in the concrete can control the efficiency of „cheap“ repair work.

LITERATURE

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