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Maintenance Strategies Based on the Assessment of Chloride Induced Deterioration

Alfred Strauss[1], Roman Wendner[1], Theodor Guggenberger[1], Konrad Bergmeister[1]
Bretislav Teplý[2], Drahmor Novák[2], Ulrich Santa[3], Carlos Costa[3]

[1] University BOKU, Vienna, Austria
[2] Technical University Brno, Check Republic
[3] Autostrada del Brennero, Italy

ABSTRACT: The maintenance of an adequate safety level of concrete bridges under their gradual degra-dation due to traffic and environmental actions during service life is an expensive, prob-lematic and questionable task. Chloride ion ingress is an important aspect of durability design and maintenance, especially in regions where winter salt application for traffic safety is common, e.g. highway bridges. Based on a case study of the Neumarkt Bridge, Italy, a feasible approach to analyze possible chloride induced deterioration illustrated will be presented. Based on laboratory analyses of specimens the chloride surface concentration was inversely determined and used for the prognosis of the corrosion propagation over time. This information served as basis for a performance assessment with respect to code based service and ultimate limit states resulting in an estimation of the remaining service life and discussion of feasible maintenance strategies.

1 INTRODUCTION

In general, concrete structures are subjected to aging processes due to mechanical, environmental, and chemical loading, among others. Consequently regular inspections need to be scheduled in order to take control of these processes. Nowadays such control and inspection programs associated with bridge structures are a common practice in most countries (RVS 1995, DIN 1999). However, these programs are mostly influenced by a subjective rating of the structural performance and relate only indirectly to the internal mechanical loading capacity of a structure. Therefore, maintenance concepts based on these inspection programs are not fully optimized with respect to the bearing capacity or reliability and the condition performance.

In addition, based on this weakness, the remaining lifetime of numerous reinforced and pre-stressed concrete structures, that are decreasing drastically due to the aggressive environmental conditions (e.g., ice salting of roads) and partly poorly executed maintenance work, are not realistically assessed. Nevertheless, it must be noted, that the lifetime of a structure is essentially influenced by maintenance strategies, maintenance tools, and the owners decisions associated with repair- investments. Therefore, the objectives of this contribution are the improvement of maintenance strategies and tools associated with inspection, degradation modelling and the numerical recalculation of the structural performance in order (a) to allow an elongation of the remaining structural lifetime, (b) to optimize the inspection, maintenance and repair periods, (c) to identify vulnerable structures, and (d) to allow an economical maintenance of an existing structure. The previously mentioned strategies and tools in maintenance have been applied to a three-span pre-stressed pre-casted bridge over the highway A22 in Italy which was demolished in 2008. In general, the applied tools contain complex methodologies comprising nonlinear modelling, stochastic modelling and degradation simulation utilizing a combination of different types of software. Both theory and software are available for the practical usage but it are rarely utilized in current practice.

2 CASE STUDY – THE NEUMARKT BRIDGE

The Neumarkt Bridge is a three-span pre-stressed pre-casted bridge over the motor highway A22, see Fig. 1. The bridge consists of four precast pre-stressed V-girders and a cast-in-place concrete deck representing a typical highway overpass of this area. Fig. 1(a-b) presents the main geometrical characteristics of the structure and the associated cross sections in detail. The main span of the middle filed is 27.00 m and of the lateral fields is 9.14 m only. Each pre-casted V-girder of the middle field is pinned and roller supported in the longitudinal direction and pinned supported in the transversal direction. Whereas the lateral buckling stability is guaranteed by the in-situ casted concrete plate located on the V-girders with a thickness of 0.14 m. Therefore, the system can be considered as an orthotropic concrete structure using V-girders as main elements. The bridge is divided into two lanes of 3.75 m and two sidewalks of 1.00 m each.

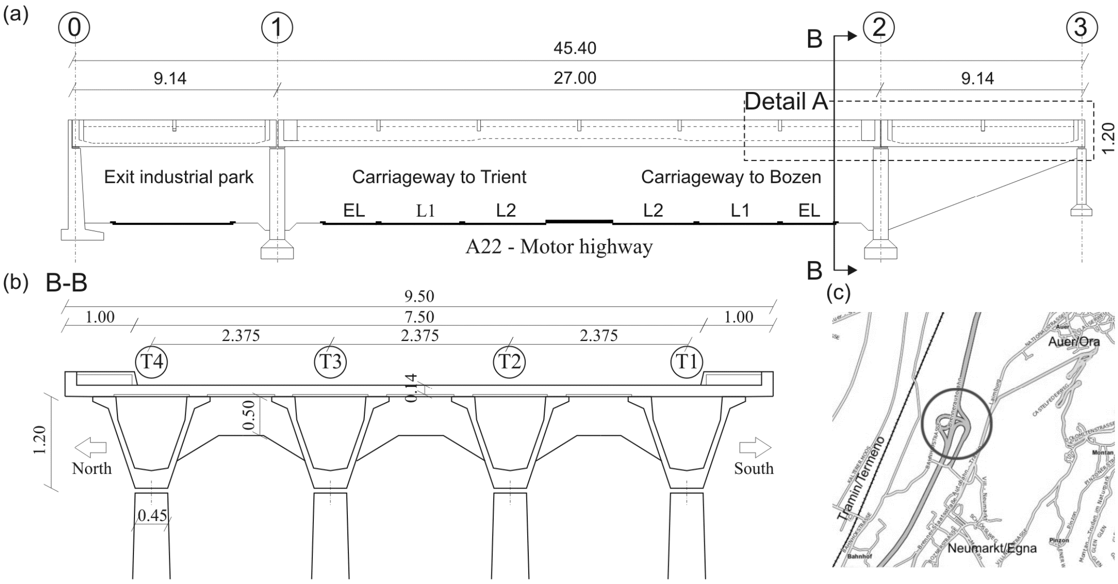

Figure 1. The Neumarkt Bridge; (a) side elevation, (b) cross-section, (c) map view

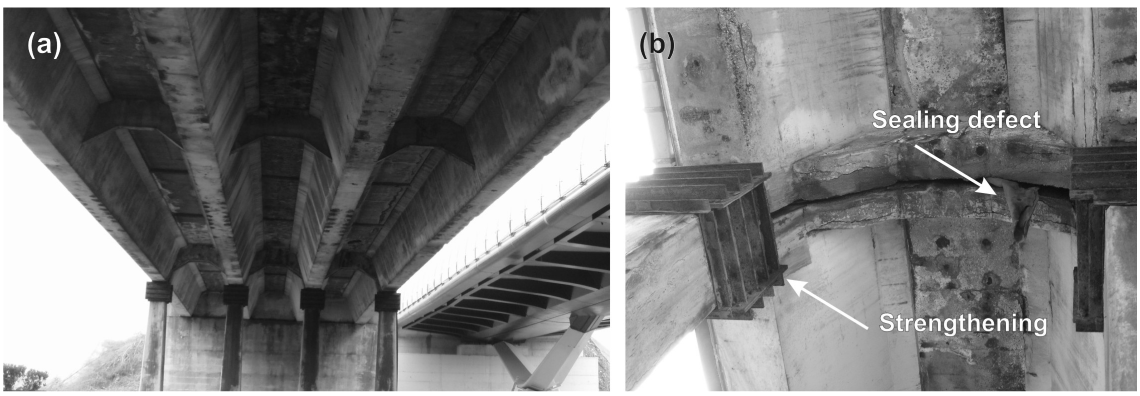

Figure 2. Documented damage (a) V-Girders, (b) sealing defect, (c) columns

2.1 The Neumarkt Bridge in course of inspection

After its 38 years of service the three span bridge, representing an overpass over the Brenner highway located in South Tirol, was highly affected by chlorides from de-icing salts. During inspection programs severe problems mainly with the sealing of the road deck and the concrete of the pillars' head were noted. This resulted in rapid degeneration of the concrete surface and reinforcement elements especially at the pillars below the expansion joints and the respective areas of the main girders. The main results of the inspections included the detection of severe problems with the sealing in 1990 and problems with longitudinal cracks on the inner side of the main V-girders and the immediate danger of massive concrete spalling in 1996, which led to provisional strengthening of the column heads in order to extend the service life. Finally during the inspection in 1999 demolishing and reconstruction of this bridge was suggested (Joris 1999).

In spring 2008 the structure was demolished after a last inspection by a research team (drilling cores and drilling powder samples were taken at various locations of bridge girders and deck) but no physical loading tests prior to the structures demolition could be performed. During the entire service life including demolition no measurements regarding the chloride feed were taken.

The Neumarkt bridge was demolished long before its planned service life was reached due to the massive damage to the columns. However the girders and the cast-in-place concrete deck at this point in time were not considered to be in critical condition. Alternatively to demolition and reconstruction of the bridge, a substitution of the columns could have been an option. In this case, the residual lifetime of the girders would have been the limiting factor. This contribution presents a feasible approach to the assessment and quantification of the remaining service life under adverse environmental conditions which could in similar cases provide the required decision basis for a structures owner.

3 ASSESSMENT OF REMAINING SERVICE LIFE

3.1 Methodology

The quantification of the Neumarkt-bridge taking into consideration the structural degradation includes the following steps: data acquisition, analysis, simulation of the surface chloride concentration and chloride ingress, prognosis of the steel corrosion, calculation of the structural response due to the expected reduction of the steel cross-section, and last estimation of the resulting reliability level respectively the remaining lifetime.

The realisation of these steps is achieved by means of the software system SARA, which is pictured in Fig. 3. This approach includes a tool for the simulation of the chloride entry over time (CATES) and a program (FREET-D) to describe the proceeding degradation (Teplý et al. 2006), e.g. steel corrosion or carbonation with respect to discrete and scattering input parameters. The structural response for the degraded structure is determined by means of the non-linear software ATENA (Červenka et al. 2002) based on fracture mechanics. The sampling of the input data sets and the analysis of the limit state functions is done by FREET (Novák et al. 2008). The whole procedure, beginning with the estimation of chloride content at various locations within the cross-section up to the determination of the reliability level is repeated for discrete points in times t_i between the initially not deteriorated state t_0 and the expected end of the service life t_n. Further information is provided by (fib 2011, Strauss et al. 2010).

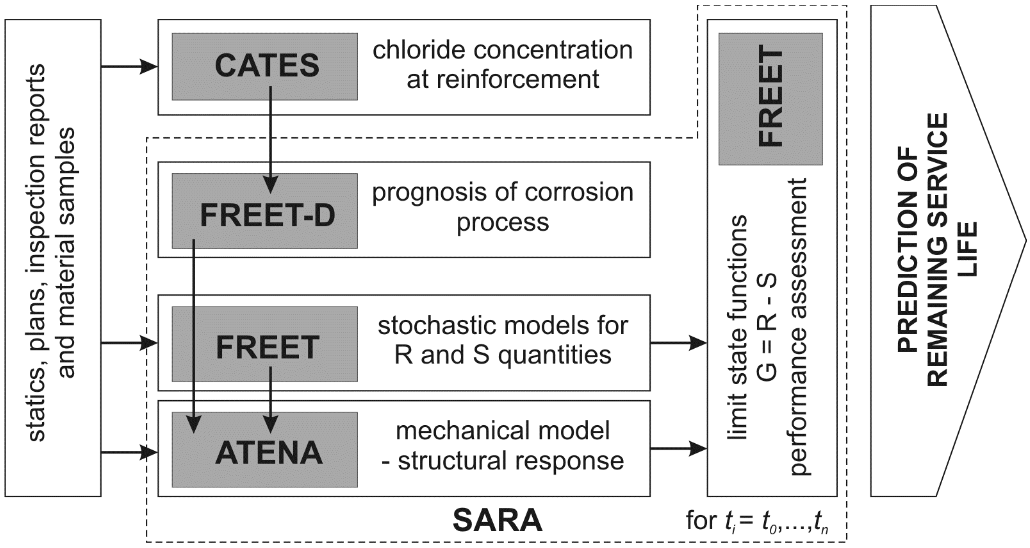

Figure 3. Phases and elements in the assessment of the remaining service life

3.2 *Sampling and laboratory analyses*

Detailed knowledge regarding the main structural characteristics is a significant input for all analyses and simulations concerning the estimation of reliability levels and remaining service life. The origin static, building plans, reinforcement plans and inspections reports, which are performed every six years, can serve as main sources for material properties, geometry, boundary conditions and loads. In contrast to this, information about chloride content as a result of deicing salt application, which has a significant impact on the deterioration of RC members, can only be obtained inversely by extracting concrete samples and inverse analyses.

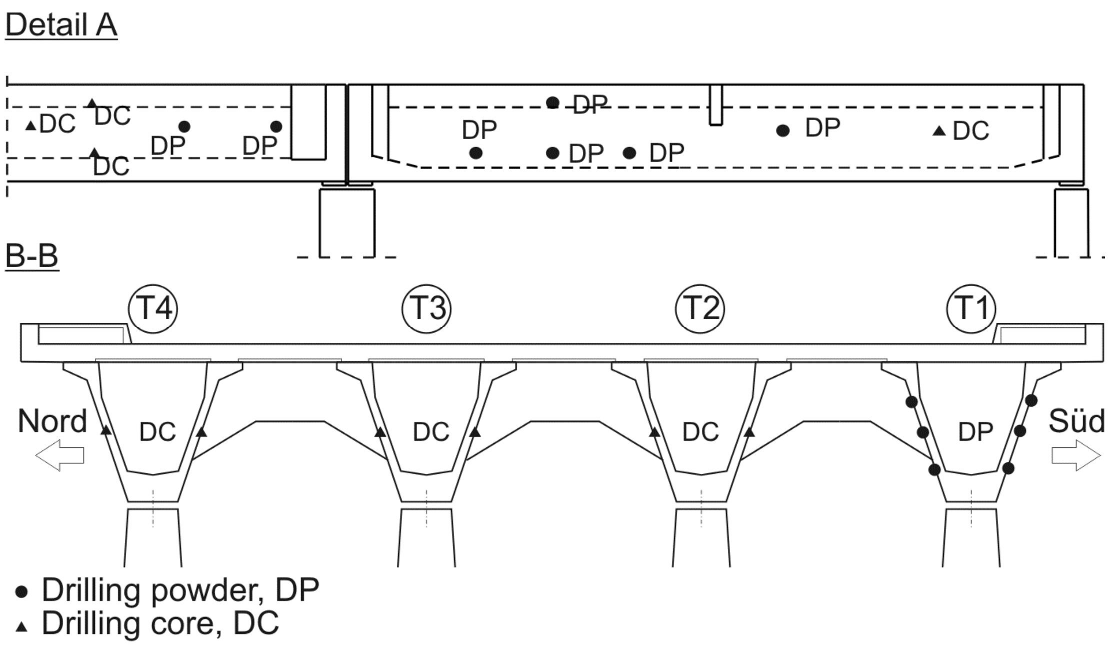

Figure 4. Sampling scheme for drilling cores (DC) and drilling powder (DP)

According to inspections and some preliminary simulations it was evident that not all parts of the girders have been equally exposed to chlorides, due to turbulence effects between the V-griders of the bridge resulting from the relatively low clearance height to the highway below and the effect of salt-water-spray.

Hence, sampling took place on the probably most affected girder T1 according to Fig. 1, see Fig. 4 focusing on the area of the first lane which is loaded by heavy traffic, respectively around the columns. Although most samples were extracted from V-girder T1, which is the only fully processed cross section according to the bore scheme from Fig. 4, samples were taken at other locations, too. Finally, drilling powder samples were collected at 14 locations along girder T1 in depth increments of 1cm. Furthermore 32 drilling cores for four complete profiles of all girders were taken. These samples served as basis for an experimental determination of chloride content depending on depth as well as the determination of pH-values.

3.3 Prognosis of chloride ingress over time

As no measurements of surface chloride concentrations were taken during operation and deconstruction of the bridge, this data had to be reconstructed from samples taken. After determining the values of chloride concentration for various depths at several locations, a 1D model (Tikalsky 2005) was applied to recalculate the surface chloride values for every location. The differing results were subsequently averaged in order to obtain a theoretical chloride feed constant in time and in agreement with the observed chloride profiles. This approach provides useful information in cases, where direct measurements are not feasible or cost efficient.

Based on the estimated surface concentrations chloride ingress over time was simulated by a Cellular automaton technique implemented in software CATES. The description of chloride ingress can be seen as an application of this method, applying the laws of mass conservation and Fick's 2nd law (Biondini et al. 2004, Podroužek et al. 2008). For this case study the diffusion coefficient is kept constant over the entire simulation period and over the cross section. The critical concentration threshold $C_{cr} = 0.065$ % is usually considered as chloride level associated with the initiation of corrosion for European climates (Duprat 2007). In this analysis C_{cr} is assumed to be deterministic in order to ensure a clear localisation of reinforcement elements endangered by corrosion.

3.4 Modelling of steel corrosion

For the assessment of the reinforcement degradation during the propagation period due to the chloride ions presence, pitting corrosion was considered to be prevailing deterioration effect influencing the performance of the Neumarkt Bridge. In a statistical analysis a model for pitting corrosion was applied (Darmawan et al. 2007, Teplý et al. 2003) finally arriving at statistical characteristics of an effective steel cross-section decrease in the course of time. The corresponding simulations were carried out by a probabilistic calculation tool called FREET-D and led to the conclusion that corrosion probably already set in after only 8 years of service. The total loss of pre-stressing steel cross-section was estimated to reach 10 % after a service life of 50 years.

3.5 Structural response of a degrading structure

Based on the simulation of the time dependent chloride ingress by the cellular automata approach reductions in the steel cross-section areas of the pre-stressing steel are obtained and can finally serve as inputs for a mechanical analysis of the system. For the determination of the mechanical performance of Neumarkt bridge, apart from deadload and pre-stressing, load model $LM1$ according to Eurocode 1 was considered. Due to the nature of nonlinear calculations, which were performed by the FE-software ATENA, all loads were applied incrementally starting with the permanent loads followed by traffic loads up to 120 % of *LM*1 load model. More information regarding the mechanical simulations is provided in Strauss et al.

3.6 *Reliability assessment and remaining service life*

To determine the safety level of a structure, it is necessary to identify the limit state functions and stochastic models for all parameters of stress S and reaction R. Moreover, the structural response at each considered age of the building has to be determined by an appropriate probabilistic approach. In case of the Neumarkt Bridge the ultimate limit state (ULS) as well as several serviceability limit states (SLS) were considered by means of deflection, crack width and concrete stress. After formulating the limit state functions in FREET, the computations were carried out in ATENA controlled by the interface SARA, and the calculation of the reliability level was done in FREET again. The assessment of the reliability was performed for the intact structure to achieve a reference, and then for ages of 38 and 58 years (30 and 50 years after the beginning of corrosion).

In Table 1 the statistical characteristics of structural response and corresponding safety level for serviceability limit states and ultimate limit state considering only 60 % of the LM1 load model are given. The reduction to 60% of LM1 aims at compensating for the idealisation to a 2D-model and the total disregard of the lateral bearing capacity provided by the deck slab..

Table 1. *Statistical characteristics of structural response and respective safety level for undamaged structure and after 38, 58 years of service (Strauss et al. 2010)*

Characteristica	Time	S			R	β
	[years]	Mean	Std	COV	Mean	
Deflection, u_z [m] ($u_{z,limit}$ = l/250)	0	-0,07	0,00	0,04	0,11	> 10
	38	-0,07	0,00	0,04	0,11	> 10
	58	-0,08	0,00	0,04	0,11	8,7
Crack width, w [mm], (w_{limit} = 0.2 mm)	0	0,07	0,01	0,17	0,20	> 10
	38	0,05	0,01	0,20	0,20	> 10
	58	0,01	0,00	0,11	0,20	> 10
Concrete stress, σ_{co} [MPa], (σ_{limit} = 0.6 f_{ck})	0	-14,12	0,20	0,01	18,00	> 10
	38	-15,34	0,17	0,01	18,00	> 10
	58	-17,10	0,12	0,01	18,00	7,5
Concrete stress, σ_{cu} [MPa], (σ_{limit} = 0.6 f_{ck})	0	1,16	0,83	0,71		
	38	2,72	0,41	0,15		
	58	2,21	0,35	0,16		

The reduction of the reinforcement in the cross section of the vertical centerline in the middle field yields to a reliability index β > 10 with respect to the 60% applied load model *LM*1 for a corrosion propagation time t = 0 (corrosion initiation) and 30 years (time of demolition). For t = 50 years β = 7.8 was determined, see Table 1 (Strauss et al. 2010).

4 OPPORTUNITIES FOR MAINTENANCE PLANNING

The results of the analyses demonstrate that the V-girders could possibly stay in service for up to 20 further years, assuming the chloride feeding on the surface of the structure as well as traffic loads remain constant. Hence, the replacement of the damaged columns, as sketched in Fig. 5, could have extended the service-life of the entire structure significantly. The progress of the condition rating depending on time is pictured in Fig. 5 considering condition levels 1-5 as usual in Austria (RVS 1995). The numerically obtained progress of the reliability level is mapped to condition rating in such a way that remaining service life as well as the respective values for known points in time correspond.

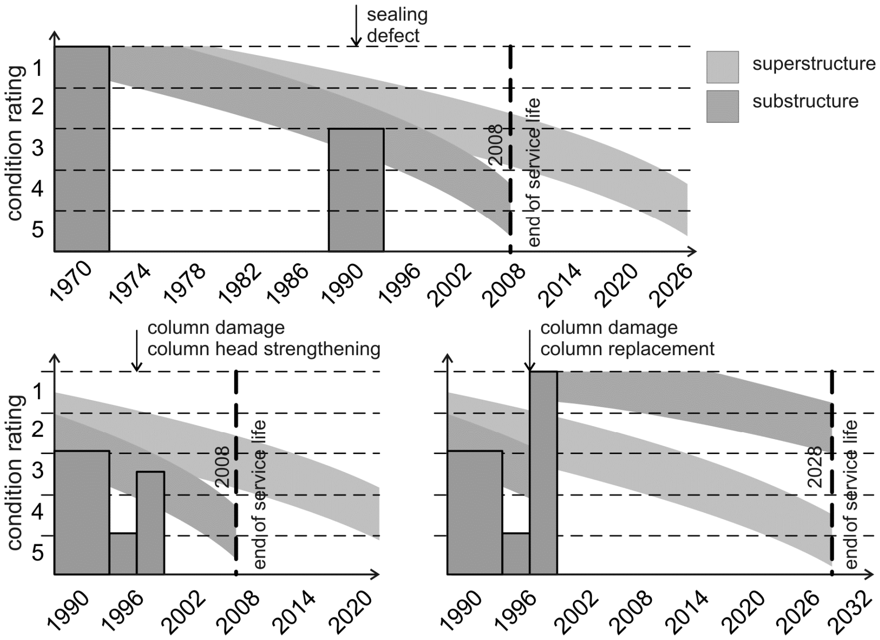

Figure 5. Condition rating over time for real and alternative scenarios (Wendner et al. 2010)

Contrary to the planned lifetime of 80 years, in 1990 serious damages on the structure were detected, hence the structure had to be categorised as level 3. However, the whole extent of damage as a result of the damaged sealing was not considered completely at this time. As a consequence no further actions were taken by the owner, and as a result the end of lifetime was expected to be reached in 2008.

During the next inspection in 1996 serious damage at the column heads due to the entrant water was detected. Therefore the heads of the pillars had to be strengthened immediately with a confinement. In spite of the strengthening, the remaining service life had further been reduced to t_R = 12 years caused by the increased deterioration rate.

If the degraded concrete columns had been replaced in 1996 instead of strengthening them, the V-beams would have become the structural elements determining the overall lifetime thus allowing the structure to be in service for several further years, which would have possibly saved costs on the long run. This analysis does not cover other considerations for the structures replacement such as e.g. an increase in traffic loads or aesthetic considerations.

CONCLUSIONS

The exposition of structures to aggressive agents e.g. de-icing salts, is becoming more and more significant in particular for concrete structures. This fact significantly influences maintenance planning in bridge engineering. In general, maintenance strategies are based on the experience of bridge engineers and practical static concepts. Nevertheless, there is a big interest in the possible extension of the remaining lifetime of a structure through the application of advanced methodologies comprising nonlinear and stochastic modeling as well as degradation simulation. Both theory and software are available but are rarely applied in current practice.

Supported by the Austrian research funding agency FFG within the EUREKA Eurostar research project RLACS and with the finacial support of the Autobrennero A22 the proposed approach could be applied on the pre-casted pre-stressed Neumarkt Bridge in South Tirol as a case study. In particular, a chemical analysis of chloride concentrations in concrete samples was carried out, based on which the chloride feed was determined by an inverse analysis. In the next step a Cellular Automata approach served for the prediction of the chloride ingress over time which finally could be mapped to a decrease in service life.

The present studies show that the application of extended numerical and stochastic techniques in structural (damage) assessment provide decision-makers with an increased knowledge about structural performance and thus new options in maintenance planning. In case of Neumarkt Bridge a significant extension of the service life based on the mechanical performance of the bridge would have been possible, if the annual chloride feed remains constant and the regional development does not lead to changes in traffic volume or traffic composition.

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