CONDITION CONTROL OF EXISTING STRUCTURES BY PERFORMANCE TESTING

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EVALUATION D'OUVRAGES EXISTANTS A L'AIDE DE TESTS DE PERFORMANCE

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SUMMARY

Performance based testing of existing structures is an important key issue to cover the task in providing safe and reliable structures. The information provided by performance testing at a specific structure is often used to confirm that the specifically required performance criteria are met. In case of non-conformity, the data provided may directly be used to prepare decisions on the extent/volume of a repair/strengthen measure.

As repair and strengthen measures are often not only of high economic relevance but also of relevance in ensuring structural safety at any part of the structure, the methods used for controlling structural condition have to be selected carefully in order to get not only the needed information at a specific location but also for the entire structure. In addition to that, the data interpretation including the data uncertainty have to be treated appropriately.

To examplify the general information given in this paper, an already built structure is introduced where condition control is/will be applied to optimise the structural life from the economic point of view without endangering the structural safety and functionality.

ZUSAMMENFASSUNG

Vor dem Hintergrund immer länger werdender angestrebter Lebensdauern unserer Tragwerke werden leistungsbezogene Nachweise zur Feststellung der Tragsicherheit und Gebrauchstauglichkeit auch während der Nutzungsphase zukünftig immer mehr an Bedeutung zunehmen. Solche Nachweise zum Zeitpunkt t_i ergeben dann, dass entsprechende Anforderungen hinsichtlich Tragsicherheit und Zuverlässigkeit gegenüber ungewollten Bauteilzuständen, die die

Gebrauchstauglichkeit zum Zeitpunkt t_i, einschränken, entweder erfüllt werden oder nicht mehr erfüllt werden. In letzterem Fall kann die Information direkt dafür verwandt werden, Entscheidungen zur weiteren Vorgehensweise zu untersützten (Instandsetzungs- und/oder Ertüchtigungsmaßnahmen).

Insofern müssen die für die Entscheidungsfindung verwandten Prüfmethoden gründlich auf ihre Eignung und Aussagefähigkeit hin überprüft werden.

Die in dieser Veröffentlichung zunächst allgemein zusammengestellten Informationen zu diesem Thema werden an einem konkreten Beispiel erläutert.

RESUME

Les tests de performance donnent une idée sur la fiabilité et la sécurité d'ouvrages existants. Les résultats des essais sont souvent utilisés pour confirmer le respect des critères de performance spécifiques demandés. En cas de non conformité, les données obtenues permettent de conclure sur l'étendue et le volume des mesures de réparation ou de renforcement.

Le choix des mesures de réparation et de renforcement à prendre, il ne dépend pas seulement de l'aspect économique, mais aussi des facteurs comme la stabilité et la sécurité de l'ensemble de l'ouvrage. Pour cette raison, les méthodes utilisées pour déterminer l'état de l'ouvrage sont à choisir soigneusement afin d'obtenir les informations nécessaires non seulement pour une partie spécifique, mais pour l'intégralité de l'ouvrage. Les données sont à interpréter de manière appropriée en tenant compte des incertitudes.

Dans cette publication la problématique est présentée à l'exemple d'un ouvrage existant où des tests d'évaluation sont et seront effectués afin d'optimiser la durée de vie d'un point de vue économique sans mettre en danger la sécurité et la fonction de l'ouvrage.

KEYWORDS: performance testing, condition control, inspection, monitoring, reliability, update

1 INTRODUCTION

Structural durability is one of the most urgent tasks to be solved for the future. It has been a key issue for many years due to its high significance in the serviceability of concrete or reinforced concrete structures, as well as to its high economic impact in the construction sector.

At present, design codes and guidelines include prescriptive requirements, to ensure sufficient durability of reinforced concrete structures. Prescriptive rules relating to environmental factors are given (maximum water/cement (w/c) ratio, minimum binder content, nominal concrete cover, etc.). Further rules (e.g. concerning curing, and air entrainment to avoid frost and freeze-deicing-salt-deterioration) complete this type of durability design. An objective, performance-based comparison between various options to improve durability as well as a limit state-related lifetime design is not possible.

A structural engineer would consider a code allowing only four loading regimes, each of which additionally being based on minimum dimension, minimum concrete strength and minimum volume of steel, to be wholly inadequate.

Although the described prescriptive design approach would be unacceptable to the structural engineer, this type of approach is accepted in daily practise for durability problems until today. However, growing durability-related problems and damages to reinforced concrete structures in the past highlight the necessity of establishing performance-based durability design (new structures) and re-design/assessment (existing structures) tools.

First promising experiences have been made in applying these performance-based design tools not only for designing new [1], but also for re-designing/assessing existing structures [2].

In the following, the role of condition control of existing structures will be elaborated against the background of already developed design/re-design tools.

2 LIFE CYCLE MANAGEMENT AND THE ROLE OF CONDITION CONTROL

In practice the technical service life of a structure is considered to be the period for which the structure or a part of it is to be used for its intended purpose with anticipated maintenance but without major repair being necessary.

The usual flow of structural life starts with structural design, proceeds with the construction phase, followed by the service life until the structure becomes demolished. Each phase may be connected to evaluation procedures, usually to regular assessment. According to Figure 1 the following stages have to be considered.

1st stage – design phase- includes the client wishes and corresponding standardisation body requirements, methods of the structural analysis, including the performance-based durability design based on deterioration models. Client wishes and standard requirements defines the structural target conditions during use expressed in terms of minimum required structural reliability. Wishes and requirements have to be transferred, specific guidelines have to be provided by the designer how to achieve the targets.

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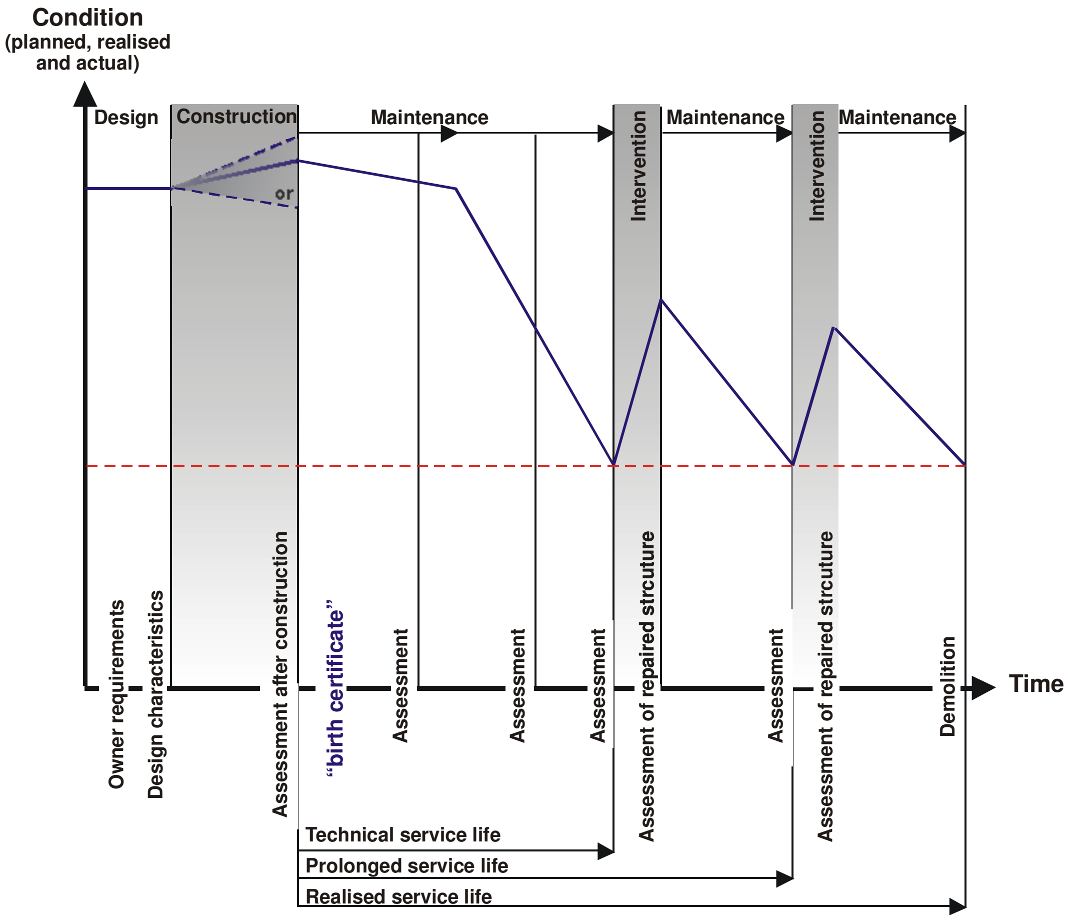


Figure 1: Structural flow from birth to exitus, adapted from [3]

3rd stage – maintenance phase – is a period in which the structure is in service, is regularly maintained but not repaired. The condition has to be controlled and assessed in order to confirm that the performance criteria are also met during operation, to manage maintenance measures or to identify the most optimal time for intervention. Often this stage includes some accepted accumulation of (minor) structural damage.

In each assessment process the actual (real) condition is expressed/translated into a structural reliability. This is done based on established deterioration models. Data of stochastic nature provided from performance testing (condition control) is taken to perform the calculation. The calculated reliability is compared to the required one. If actual reliability is less than required, intervention could be the consequence.

Beside the precision of the deterioration model, not only the determined data itself but also the determined quality of the data will have a major influence on the calculated structural reliability. Consequently, it depends decisively on the quality of condition control data, when a structure with specific (real) condition is evaluated.

4th stage – intervention/repair – to elongate structural life on an acceptable condition level (reliability) repair or strengthening of the structure may be necessary. The determined condition of the repaired/strengthened structure should be used for evaluation of prolonged service life.

As illustrated in Figure 1, to run a structure safely on an acceptable condition level, structural condition has to be controlled during all phases/stages. The data determined by performance testing on existing structures is used for example to estimate the residual service life of existing structures and/or to evaluate conformity with performance design data, i.e. for actions and/or material and/or product properties. In case of non-conformity the data is often taken to decide upon extent/volume of a repair/strengthen measure.

As a decision with regard to the necessity and, if necessary, with regard to the required extent of a repair and strengthening action is often of high economic impact, the information, the decision has to be based on, must be reliable. Consequently, the uncertainty of provided information have to be treated appropriate.

3 LEVEL OF PERFORMANCE TESTING

Condition control of reinforced or pre-stressed structures by performance testing is expected to assess a wide range of possible damages (see Figure 2). To confine the operative and hence the cost expenses, condition control is normally partitioned into different levels of performance testing, i.e. different levels of investigation [4].

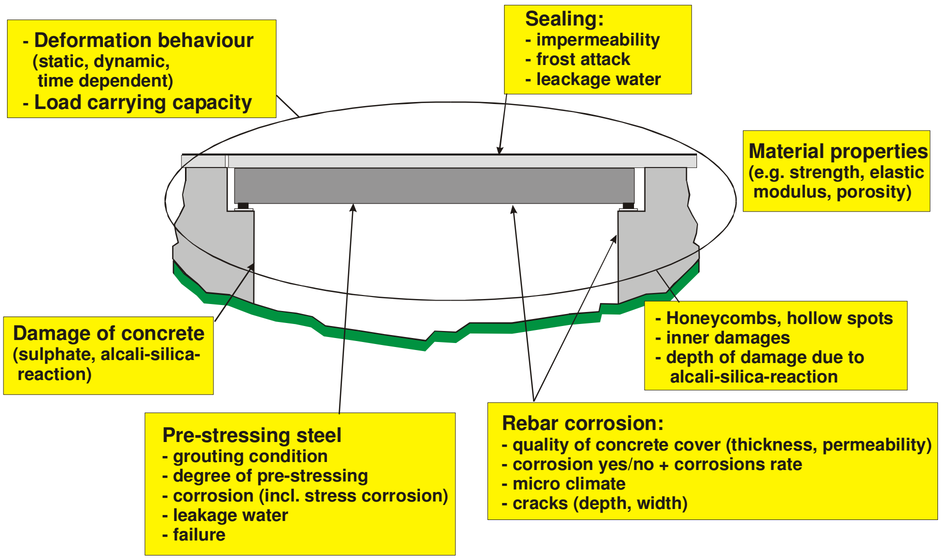


Figure 2 : Condition control at pre-stressed structure: required performance testing in regard to possible damages [5]

As a first step there should be action in regard to **preparation of assessment activities**. This step includes gathering of information about the history of the structure, preliminary visit, planning of assessment and hence collecting all available structural, environmental und service information.

Table 1: Example of possible damages and their influence on the performance characteristics of the structure [6]

Level of Investigation	Characteristics		
	Load Capacity	Serviceability	Durability
Visual Inspection	Cracks, deformations, buckling	Cracks, deflections, movements, movement ability	Cracks, honeycombing, damp patches, stalactite formation
Basic Testing	Strength, ductility, fatigue strength, corrosion	Abrasion, discoloration, static and sliding friction coefficients (eg. For bearings)	Corrosion, carbonation, chloride content, frost resistance
In-Depth Inspection	Failure of prestressing cables, large residual deformations	Deflection, vibrations	Forms of corrosion, vibration frequencies

The next step of condition control is the **routine inspection** which normally includes visual inspection and basic testing. **Visual inspection** should focus on the following points:

- verification of the gathered information in the first step;

- appearance and differences in colours of the concrete surface,
- presence of cracks, their appearance and patterns,
- (superficial) deterioration of the concrete,
- exposed rebars, signs of corrosion,
- deformation of the structure,
- inspection of coatings, sealings, etc,
- presence of humidity or water, leakages etc.

Table 1 gives some examples on possible findings depending on the level at which inspection and assessment is being carried out and how these findings may influence the performance characteristics of the structure [6].

The **basic testing** of structures can be subdivided in non-invasive, non-destructive and marginal destructive. The following simple tests should permit the checking of the visual inspection and therefore estimate the importance of the visual observation:

- non-destructive testing:
  - delamination mapping;
  - concrete surface hardness (rebound hammer);
  - concrete cover depths and reinforcement location (at randomly selected locations);
  - crack survey.
- marginal destructive testing:
  - carbonation depth (at randomly selected locations),
  - chloride content (at randomly selected locations).

The routine inspection (as a combination of visual inspection and use of basic testing) results in a simple condition evaluation as well as in a decision on the extent and methods for an in-depth investigation.

In-depth inspections are essential (1) to complete or complement the routine inspection when necessary or when particular aspects were detected which need further inspection or testing or (2) according to the extent of deterioration or defaults, to perform special tests needed to assess the structure, to predict residual service life.

The tests can be classified to the required information in regard to:

- Mechanical properties of the concrete:
  - concrete compressive strength,
  - concrete tensile strength,
  - pull-off strength,
  - ultrasonic pulse velocity.
- Durability properties of concrete:
  - chloride content and its depth dependent distribution at selected locations,
  - carbonation depth at selected locations,
  - concrete cover,
  - absorption,
  - (water, air) permeability,
  - porosity;
  - chloride diffusion coefficient,
  - petrography (macro analysis, micro analysis, air void analysis),
  - cracking (e.g. causes, widths),
- Mechanical properties of the reinforcement:
  - steel tensile test,
  - fatigue testing.
- Assessment of corrosion (rate) of the reinforcement:
  - determination of the steel removal (invasive testing),
  - potential mapping,
  - resistivity mapping,
  - anodic pulse measurements,
  - linear polarisation resistance measurements,

  - Electrochemical Impedance (EIS) and Electrochemical Noise (EN) measurement,
  - radiography,
  - long-term corrosion monitoring (e.g. Anode Ladder).
- Properties of the pre-stressing:
  - radiography,
  - exploratory hole drilling,
  - ultrasonic testing,
  - radar,
  - impact-echo method,
  - stress release method (in situ measurement of the pre-stressing forces).
- Structure assessment of geometry, action, static and dynamic response:
  - photogrammetric methods,
  - monitoring systems (deflection, rotation, vibration, strain),
  - static load tests,
  - dynamic testing.

In general, in given specific cases only some of the listed tests for in-depth inspections are required. For example, if in a routine inspection it was assessed that the carbonation or the chloride penetration had not yet depassivated the reinforcement, tests to assess the steel corrosion rate are irrelevant. Therefore, it is essential to perform the testing in a coordinated procedure: beginning with an overview assessment accompanied with a low precision (visual inspection), followed by a more insight testing with decreased uncertainty of the measurement (basic or in-situ /in-depth inspection) at selected areas and finalised by laboratory testing of selected spots, see Figure 3.

In case of condition control in regard to possible chloride induced corrosion of the reinforcement the following steps of gradually increased level of performance testing is recommended:

- 1st step: visual inspection in combination of gathering information,
- 2nd step: potential mapping at areas of potential risk,
- 3rd step: determination of chloride profiles at selected spots of interest (according to potential mapping) or further accompanied testing (e.g. resistivity measurement) (see Chapter 4.3),
- 4th step: exploratory hole drilling and determine the extend of steel removal due to corrosion in order to confirm the evaluated data.

This coordinated testing procedure assures a high significance of the performance testing as it combines overview information with a high precision of the measurement.

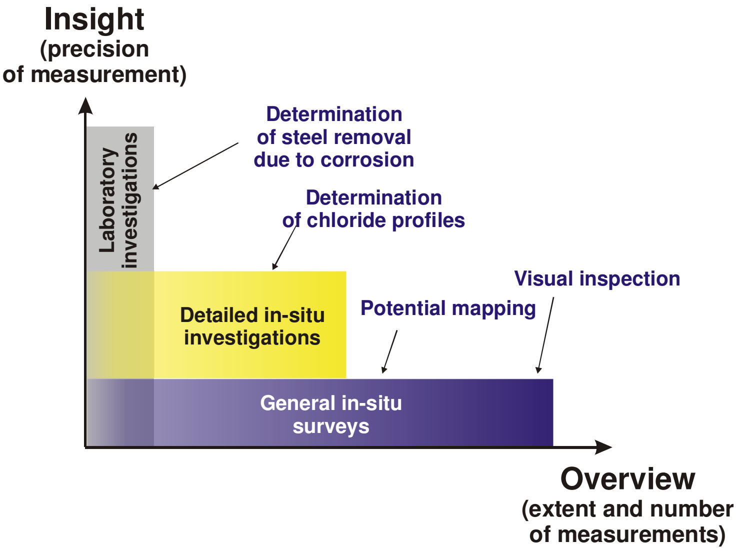
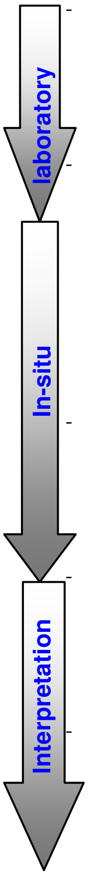


Figure 3: Type of information in dependence on the different levels of investigation

4 RELIABILIY OF CONDITION CONTROL

4.1 General

To get information about the actual condition of existing structures performance testing is conducted. However, the test method applied and hence the gathered information is to some extend uncertain. The following sources of uncertainty are existent:



- uncertainty caused by the **testing method** itself (e.g. the accuracy of the concrete cover indicated by the covermeter under laboratory condition),
- uncertainty caused by **systematic interferences** of the testing method (e.g. the influence of the temperature on the resistivity measurement), which in some cases can be excluded calculatively (e.g. using Arrhenius-equation to exclude the temperature-influence) and which are predominantly caused by in-field-situation of the measurement,
- uncertainty caused by **random interferences** of the testing method (e.g. water content of the concrete while conducting potential mapping), which are also predominantly caused by the in-situ-situation),
- uncertainty caused by **human factor influence**, which is actually part of the interferences both the systematic ones (e.g. work experience) but also the random ones (e.g. tiredness of the inspector),
- uncertainty in **data interpretation**, which normally happens back in the office after gathering measuring values and which is strongly dependent on the working experience of the interpretator and the significance of the chosen testing methods.

Determining a measuring value as a result of the in-situ performance testing (like concrete cover [mm] or chloride content [wt.-%/Cement]), this value is connected with an accumulated uncertainty due to the aforementioned elements (except the interpretation), which according to the definition of the “Guide to the Expression of Uncertainty in Measurement”, [7], is called “**uncertainty of measurement**”. This uncertainty of measurement in combination with the uncertainty in interpretation affects the reliability or - to use the statistic synonym – the “**probability of detection**” (*POD*) of a certain condition.

The probability of detection can be illustrated with the example of potential mapping. The testing person, the inspector, has to draw a conclusion whether the reinforcement is corroding in dependence on the potential values. Four cases are possible:

- Case 1: the inspector concludes that the rebars are corroding and there is indeed corrosion of the reinforcement (correct alert).
- Case 2: the reinforcement is corroding but the inspector does not assess the corrosion (wrong all-clear).

- Case 3: there is no corrosion but the inspector concludes that the rebar is corroding (wrong alert).
- Case 4: there is no corrosion of the reinforcement and the inspector assesses the passivity of the reinforcement (correct all-clear).

It is easy to understand that both wrong conclusions can have severe consequences: either a repair is initiated although it is not necessary or a wrong all-clear may bring further damages and additional costs in future. Therefore it is essential for the inspector to know the probability of occurrence the four cases. The combined probability of cases 1 and 4 are normally called the probability of detection (*POD*), whereas the probability of wrong decision is hence *1-POD*. The smaller the uncertainty in measurement, the higher *POD,* the higher is the reliability of condition control.

As mentioned before the value of the uncertainty in measurement is dependent on the uncertainty of the method itself and on interference effects including the human factor. The accuracy of the testing method at specific measurement conditions can - in the majority of cases - be gathered from the instruction manuals or literature. In contrast to that the interferences or disturbances are difficult to consider. For example to assess whether the reinforcement is corroding or not by conducting potential mapping has a low probability of detection as disturbance effects (like water content of the concrete, concrete cover, oxygen content…) can have significant impact on the measured potential. Thus the evaluation criteria given in ASTM-C 876 as probability of corrosion have to be used very cautiously. The interpretation of potential mapping should therefore always be compared with the interpretation of the results of other inspection techniques to increase the significance measured results (see Chapter 4.3).

4.2 Human Factor

Besides the measuring technique and disturbance effects a significant uncertainty in measurement is caused by the testing person, the inspector itself. These **human factor influences** are physical factors like tiredness, exhaustion, illness but also psychological factors like motivation, sensitivity against stress, fear, worries etc. Of course the inspector’s experience and education have a tremendous impact on the reliability of the gathered data and their interpretation.

The influence of the human factor on the reliability of condition control is supposed to be affected by the level of investigation: for visual inspection the human factor has more impact on the assessment than for laboratory investigations. For visual bridge inspection the influence of the human factor has been tested by a federal highway study [8]. In total 49 bridge inspectors with different work experiences carried out visual inspection as routine inspection on seven bridges. They had to give ratings on the structural condition assigned to the bridge deck, superstructure and substructure. These condition ratings give an overall measure of the condition of a bridge by considering the severity of deterioration in the bridge an the extend to which it is distributed throughout each component. The ratings assigned to each element are based on a standard set of definitions associated with numerical ratings between zero (failed) and nine (excellent condition). The results of the study including a reference rating, which is the condition rating given to each element through assessments of Federal Highway Administration are given in Table 2. A statistical analysis of the results using the t-test examined whether the two ratings (inspector's and reference's) were statistically different. The results indicate that in most cases, the average inspector condition ratings are statistically different from the reference rating, see Table 2.

Additionally in-depth-inspections have been carried out at two bridges, showing that most of the inspectors did not assess severe fabrication errors, crack indications, bolt defects, whereas paint system failure and general corrosion had been detected by most of the inspectors.

Table 2: Results of the Federal Highway Study on reliability of visual bridge inspection – Routine Inspection Condition Rating [8]

Bridge	Element	Rating			Result of the t-test
		Average	St. Dev.	Reference	
B521	Superstructure	5.9	0.78	5	Pass
	Substructure	6.1	0.79	6	Fail
	Deck	5.8	0.81	5	Fail
B101A	Superstructure	4.2	0.77	4	Fail
	Substructure	4.3	0.76	4	Fail
	Deck	4.9	0.94	4	Fail
B111A	Superstructure	4.6	0.86	4	Fail
	Substructure	5.5	0.77	5	Fail
	Deck	5.2	0.92	4	Fail
B543	Superstructure	5.3	0.88	5	Fail
	Substructure	6.1	0.89	6	Pass
	Deck	4.8	0.94	5	Pass
B544	Superstructure	5.8	0.72	6	Fail
	Substructure	5.3	0.83	6	Fail
	Deck	4.5	0.74	4	Fail
Route 1	Superstructure	6.7	0.66	7	Fail
	Substructure	7.2	0.57	8	Fail
	Deck	7.1	0.53	7	Pass
Van Buren	Superstructure	6.8	0.64	7	-
	Substructure	6.7	0.62	8	-
	Deck	5.8	0.92	7	-

As a conclusion of this study, it is found that the result of the visual and routine inspections, condition ratings, element-level inspection results, inspection notes and photographs are used with significant variability. For in-depth inspections, it appears that when an in-depth inspection is prescribed, the inspectors may not yield any findings beyond those that could be noted during a routine inspection.

4.3 Significance of performance testing methods

The aim of condition control is to determine whether the required performance criteria are met (or not). To ensure a high reliability of the condition control it is essential to choose a performance testing method with a high significance of information needed as different performance testing methods have each their characteristic merits and deficiencies. Thus it is necessary to know which information can be gathered from each of these methods and as consequence to choose a suitable testing method.

An effective way to determine a suitable performance testing method is first to narrow down the possible condition - and thus the essential information - to expected and relevant information (**problem-orientated approach**). By gathering information on the history of the structure, used materials, environmental etc., expected conditions or unwanted conditions such as certain faults/damages can be deduced. By analysing the structural behaviour of the structure statistically those conditions (with linked faults/damages) can be specified which are relevant for the structural safety and functionality. The **method-orientated approach** enables to confine those conditions (and thus faults and damages), which according to the scientific knowledge and the state of the art are not detectible or identifiable. The combination of problem-orientated and method-orientated approach enables then to choose a testing method which enables to assess expected, relevant and identifiable conditions and is therefore effective with a high significance. Figure 4 (left) shows the triangle of conflict in the choice of finding an effective testing method [9].

A single testing method is likely not to cover the whole range of expected and relevant conditions. To increase the significance of information a combination of different performance testing methods is reasonable. Figure 4 (right) shows that combining different testing procedures A to D covers more of the effective area of the triangle and therefore increases the significance of the performance testing.

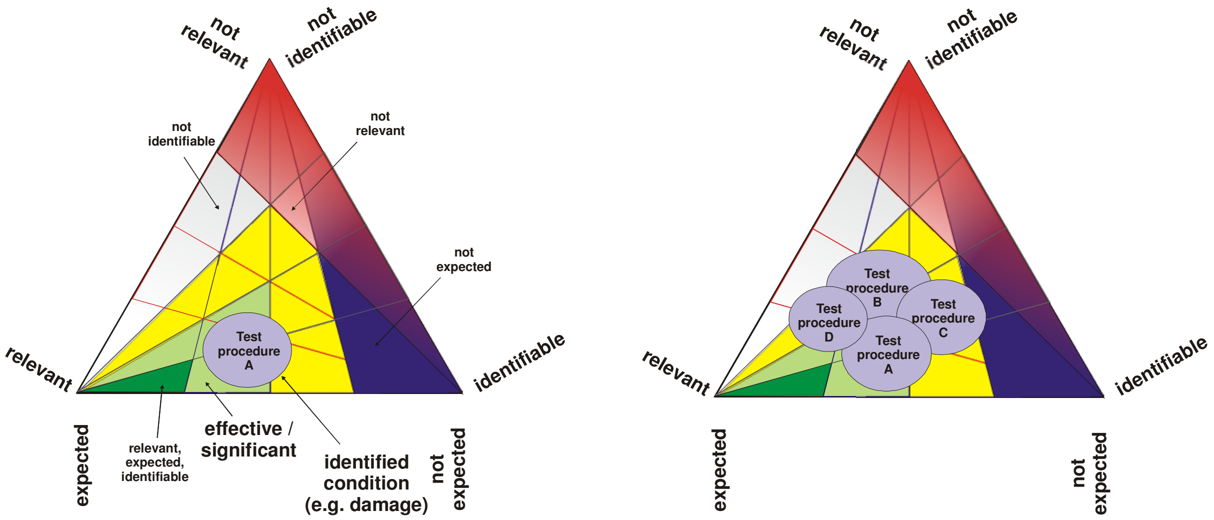


Figure 4: Significance of testing method to identify specified condition;
left: choice of testing method to assess expected, relevant and identifiable conditions;
right: combination of testing methods to increase the area of identified conditions

An example shall illustrate the significance of the testing method and the increase by combination of different methods: as mentioned before, sole potential mapping has a low significance to detect corrosion of the reinforcement as numerous interferes have strong impact on the measured potential. Thus the span of potential values in an uncertain range according to ASTM-C 876 is rather wide (-350 to -200 mV vs CSE). Even in the range of measured values >-200 mV the probability of corrosion is indicated with 10 %, i.e. that the probability of a “wrong all-clear” of the inspector is rather high. This high probability can be explained scientifically that in some cases of low water content, high concrete cover or dense concrete mixture, values of >-200 mV are measured although the reinforcement is corroding. Introducing additionally testing methods like determination of resistivity of the concrete or permeability (as a measure of the water content and or the density of the concrete), the concrete cover, the chloride content, the pH-value or the corrosion rate (using pulse- or LPR measurements) these interferes can be evaluated and thus the probability of a “wrong all-clear” is decreasing.

Analogical measuring a potential of < -350 mV the probability of corrosion is confined of

90 %, as the probability of “wrong alert” due to water saturated concrete conditions and hence deficiency of oxygen is not marginal. Steel in oxygen-deficient environment can show very low potentials although no active corrosion is occurring [10]. As the potential value is in a lower degree influenced by the chloride content of the surrounding the probability of “wrong alerts” in this case the determination of chloride profiles will not help significantly to reduce the probability of a “wrong alert”. In this context Figure 5 shows the relation between steel potential, wetness and chloride content of the concrete. The potential decreases with increasing wetness and chloride content. The higher the water (the lower the oxygen access) the lower is the expressiveness of the potential measuring.

An increase of the significance of the potential mapping can be achieved by combination with resistivity measurement (determination of water saturation of the concrete), determination of the corrosion rate or by exploratory hole drilling and determine the corrosion condition at the steel surface.

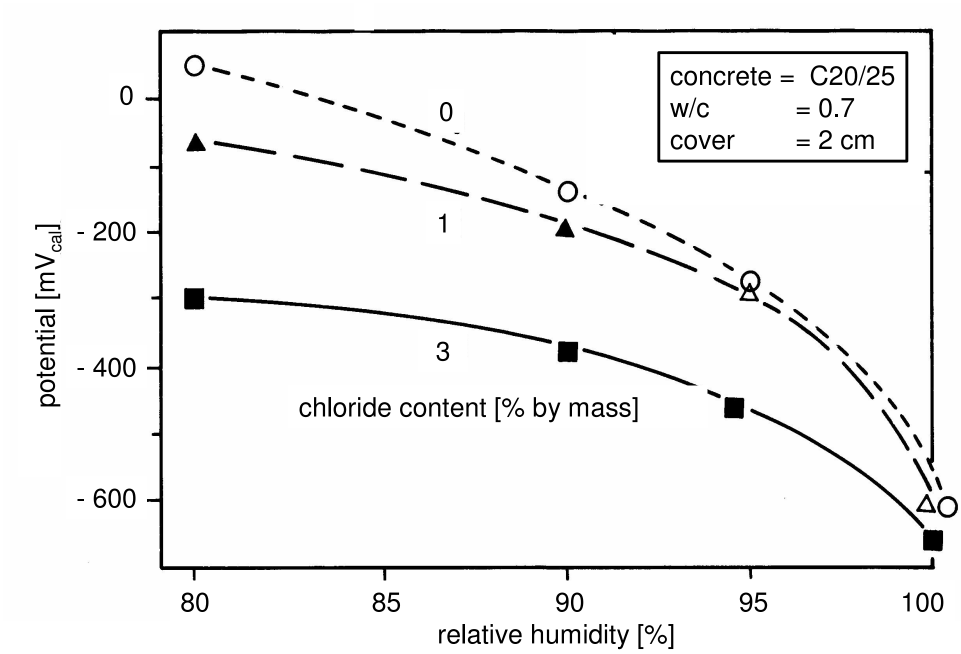


Figure 5: Potential of steel in concrete in dependence of wetness and chloride content [10]

Figure 6 shows the significance of the performance testing and thus the probability of detection at the example of corrosion of the reinforcement in dependence of as well the level of investigation as for combination of different testing methods.

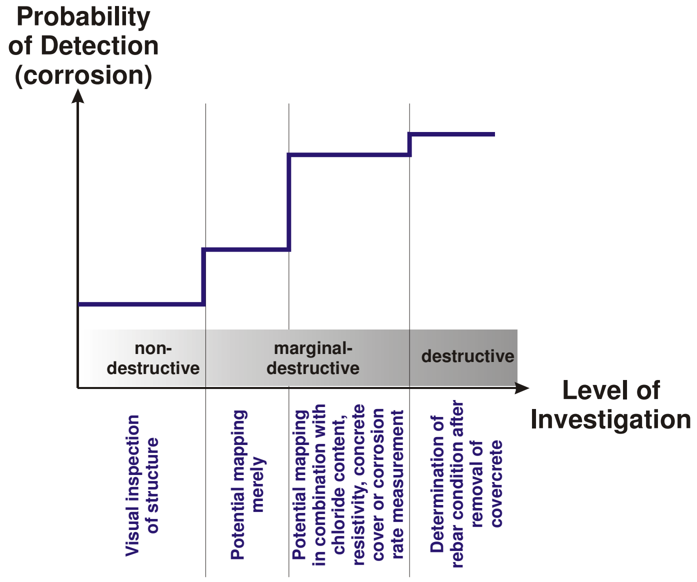


Figure 6: Significance of testing method and thus probability of detection of corrosion in dependence of level of investigation and by combination of different testing methods

5 EXAMPLE: THE ROLE OF CONDITION CONTROL IN LIFE CYCLE MANAGEMENT

In Munich, Germany, a new football arena was built. In 2006 the world championship has been opened there. In order to provide an adequate infrastructure for visitors, the arena is connected to the underground railroad (public transport). For those who intend to come by car, the arena is connected to the highways A9 and A995. To provide adequate parking space, a huge multi-storey car park with 11,000 parking spaces, the biggest in Europe, was constructed.

The car park consists of altogether four parking decks, see Figure 7. Three of them are reinforced and pre-stressed, one of them, the bottom one, is plain concrete. The reinforced and pre-stressed top deck is a pedestrian area only. Via the top deck, visitors will reach the arena by foot.

Figure 7: Side view of the multi-storey car park (source: www.allianz-arena.org)

As de-icing salts, often in combination with frost attack are expected on the horizontal parking deck surfaces, the design of the three parking decks should provide adequate durability against chloride induced corrosion and freeze-thaw attack. As the dimension of the multi-storey car park is about 425 m in length and 152 m in width a preventive coating of all three decks is very costly (extra investment costs of about 7,500,000 €).

Considering that only in case of football matches the car park is frequented (event dependent utilisation), it was decided, that a preventive coating of the whole area of all decks at this early time is from the economical point of view not justifiable (the service life of coatings is expected not to be longer than about 15 years).

The design task (stage 1 of Figure 1) was to develop a solution in reducing the high investment costs for a complete coating without falling below minimum accepted structural condition levels, in other words without putting structural functionality and load bearing capacity at risk during life. The target service life was set to $t_{SL} = 50$ years (owner requirement).

In the design stage, it was assumed, that an excellent concrete quality in combination with an adequate concrete cover in an uncracked situation can provide acceptable resistances against chloride ingress and frost attack also when the structure is uncoated. Only in the surface areas, where cracking has to be expected an extra protection is definitely needed.

To minimise cracking, the following measures have been taken: three expansion joints divide the car park into four sections. In addition, the decks are supported by pendulum columns, enabling axial deformations (temperature, drying shrinkage) without inducing restraint and separating cracks. Only in the vicinity of supported areas, load induced bending cracks have to be expected.

This special situation offered to differentiate between cracked (load induced bending cracks) and uncracked deck surfaces, cp. Figure 8. The approach is to protect load-induced cracked surfaces from environmental load S-1 by regularly inspected and maintained crack-bridging coating R-1 (coating: avoidance of deterioration approach) and to design uncracked surfaces in a mode that S-2 induced deterioration (i.e. reinforcement corrosion and/or frost deterioration) is not avoided but carefully controlled and limited to target values (effective barrier: concrete cover), see Figure 8, R-2.

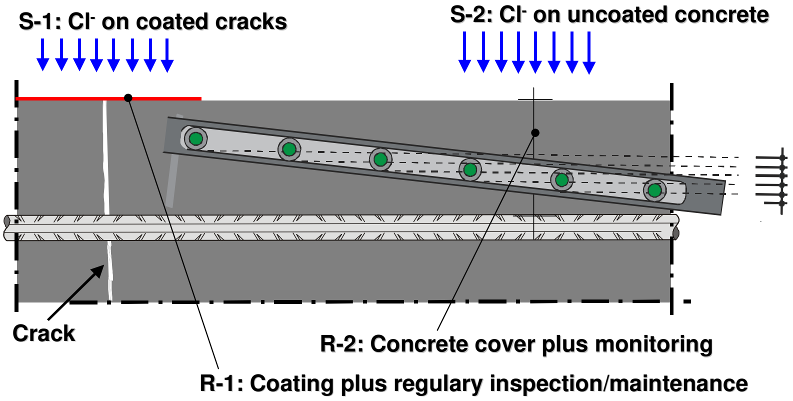


Figure 8: Design principle for cracked and uncracked areas

In consequence, all surfaces/zones showing bending moments and corresponding tension stresses according to amount above the 5 % quantile of the axial tension strength of the deck-concrete (potentially cracked zones) were coated preventively, see Figure 9.

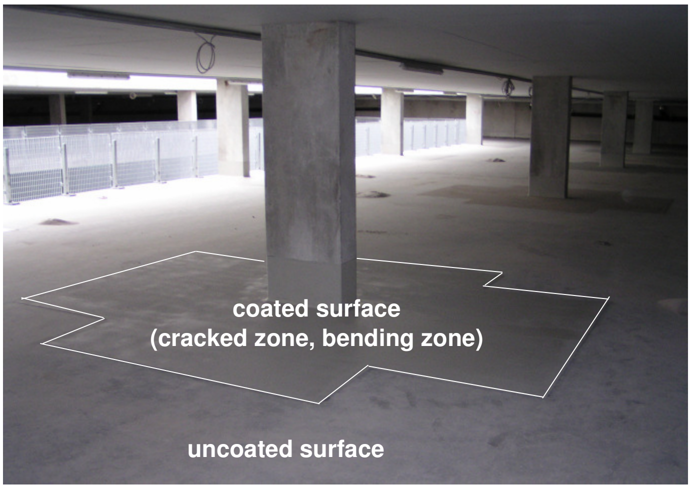


Figure 9: Locally coated surfaces

All other surfaces (potentially uncracked zones) remained uncoated, see Figure 9. Taking into account, that the nominal concrete cover was already fixed to nom c = 45 mm only the concrete mix could be optimised to achieve an adequate structural durability against chloride induced corrosion. In consequence, the optimisation task was to find a mix which provides an acceptable high chloride penetration resistance (low ingress of chlorides) in combination with a sufficient high resistance against freeze-thaw attack (suitable in avoiding deterioration at all).

The recommended range of ISO 2394 (serviceability limit state to the end of service life) is between $\beta = 0$ (reversible) and $\beta = 2.3$, often $\beta = 1.5$ is applied.

The performed service life calculation was based on specific design assumptions regarding concrete cover and chloride diffusion coefficient. To met the design assumptions of concrete cover and chloride diffusion coefficient, guidelines were given with specified requirements in regard to cover (mean value and standard deviation to be achieved) and concrete quality (composition and the origin of constituents to built in).

The result of the design calculation is given in Figure 10. The result was a reliability of $\beta = 1.0$ at time $t_{SL} = 50$ a. How to perform a full probabilistic and performance-based service life design is described [1], more background information can be taken from [11], [12] and [13]. With increasing time of exposure, the probability of depassivation (here defined as failure) will increase as the chlorides continuously penetrate into the structure. Further, the higher the probability of depassivated reinforcement the lower the reliability against depassivation in terms of β.

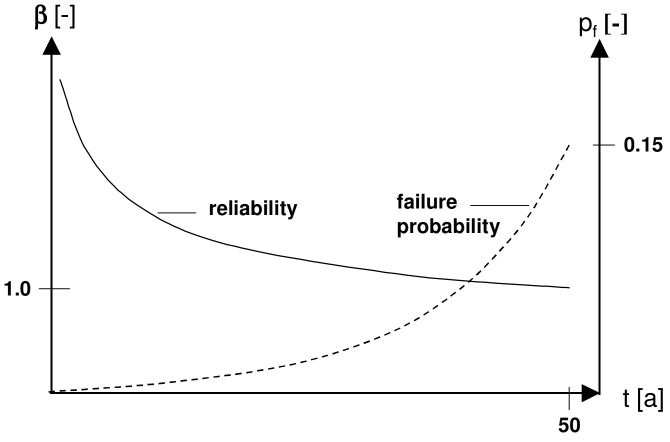


Figure 10: Reliability β, failure probability p_f, that reinforcement installed nearest to the deck surface become depassivated

Within the construction phase not only the material performance with regard to chloride diffusion resistance but also the achieved cover was continuously measured and documented.

Both quantified measures (measured geometrical quantity and measured material compliance) were taken to re-calculate the probability of onset of corrosion of the reinforcement (fully probabilistic durability design) and the reliability that reinforcement remain passive, respectively. The uncertainty of measurement were taken into account. It turned out, that the overall design target ($\beta = 1.0$ at time $t_{SL} = 50$ a) was met.

To operate the structure safely and to ensure the functionality a condition control plan was established.

The condition control plan consists of:

- What types of inspection/monitoring shall take place
- What components of the structure to be inspected/monitored
- The frequency of condition control

- The performance criteria to be met
- Possible documentation/interpretation of the results
- Action in the event of non-conformity with the performance criteria

Inspection, especially within the first series is mainly made to verify that areas supposed to be uncracked are in fact uncracked (verification of design assumption). If not, a crack-bridging coating (intervention) is applied immediately. Follow-up inspection activity will be extended by applying non- and marginal-destructive test methods in addition (potential mapping, determination of chloride profiles). Hereby, the spatial spread of an expected unwanted condition can be determined with a corresponding POD (potential mapping). The uncertainty of the chloride profiling method have to be considered as well.

The locally installed monitoring system provides information about depth dependent corrosion activity at specific locations. Like all methods, also this method includes a specific POD. Sensors were installed at different locations, mainly in low points, expected hot spots with regard to reinforcement corrosion and frost deterioration. The sensors and the principle of the monitoring system are described in [14]. The information that will be provided by the sensors at low points is: How deep the depassivation front develops with time, see Figure 11. This information will be used to update the durability calculation continuously and in addition to that to ensure an early-warning-system.

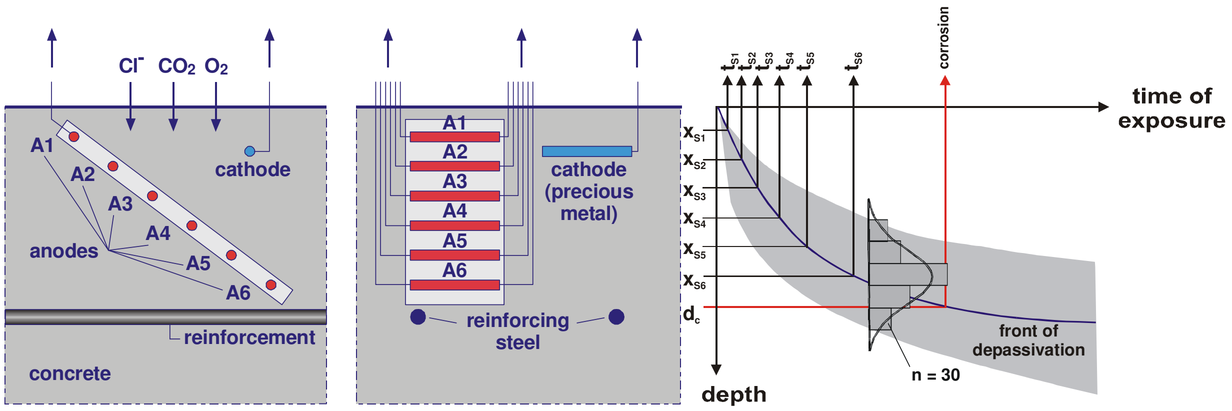


Figure 11: Functional principle of the corrosion monitoring sensor "Anode Ladder" with development of the depassivation front, schematic showing, qualitative information expected from the installed corrosion monitoring sensors (right)

If the measured depth of the depassivation front at time $t_{insp.}$ is lower as a-priori expected or as soon as the expected depth at time $t_{insp.}$ will be confirmed by the sensors, the reliability (serviceability) of the structure is increased. On the other hand, if the environmental load is underestimated (a-priori) the recalculated reliability of the structure will be reduced compared to the original a-priori calculation. The same cohesions apply to the updated failure probability. One consequence of the updating procedure, a higher reliability compared to the a-priori calculation, is formally indicated in Figure 12.

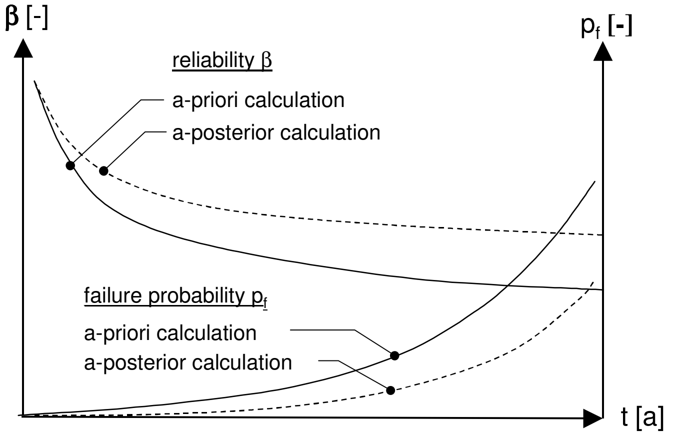


Figure 12: Reliability β, failure probability p_f, that reinforcement installed nearest to the deck surface becomes depassivated, a-priori and a-posterior calculation

From the continuously updated information (monitoring, inspection) about the probability of occurrence that the reinforcement is starting to corrode, an optimal point in time can be determined to apply a preventive coating. The coating has to be applied accurately timed, so that a possible redistribution of chlorides (equalisation of concentrations) after application of the coating does not lead to (temporary) corrosion of the reinforcement/pre-stressing bars.

Due to the expected low frequency of the parking deck during operation (event depending utilisation) it is expected that the durability of an uncoated but corrosion-optimised structure is much higher than experiences show for parking decks located in congested urban areas.

Depending on the regularly controlled ingress of chlorides one or two coating measures and their associated costs may be saved without any restriction in safe operation if compared to the situation preventive coating from the beginning and renewal every 15 years.

6 GAPS, OUTLOOK, NEEDED RESEARCH

If a structure is solely designed in terms of reliability indexes β an elaboration and a broad consensus regarding acceptable or target reliability levels β for both structural safety and durability is urgently required. For structural safety (ultimate limit state, ULS) for example recommendations were given in EN 1990 [15] or in ISO 2394 [16]. If serviceability (Serviceability limit state, SLS) is concerned, recommended minimum values for β are between $\beta = 0$ and $\beta = 2.3$, cp. ISO 2394 [16], often $\beta = 1.5$ is applied. However, instead of suggesting single β values, these acceptable values should urgently be expressed as a range of β values that depend on the hazard scenario, on economic constraints and on the expected consequences of failures.

Future work in the area of research and development is mainly to compile or to proceed with the activities regarding scientific modelling. This task is to be done in conjunction with further activities regarding harmonisation and increasing of precision of already existing condition control methods.

Finally, future research should also contribute to improve the tool condition control. Hereby not only the single performance test method itself (further development of non-destructive test methods, information about measurement uncertainty in dependency of interference effects,….) but also the whole condition control management (how to deal with spatial variability, relevance of method combination,…) can be improved significantly.

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