Developing a Life-Cycle Management System for Reinforced Concrete Buildings based on Fully-Probabilistic Deterioration Models

K. Lukas[1], A. Borrmann[1], M. Zintel[2], T. Mayer[2] and E. Rank[1]
[1]Chair for Computation in Engineering, Technische Universität München, Germany
[2]Centre for Building Materials, Technische Universtät München, Germany

Abstract

In a current research project we are developing a software tool for the predictive life-cycle management of reinforced concrete structures. There are two main novelties in our approach:

On the one hand we integrate non-destructive inspection techniques in combination with full-probabilistic deterioration models, thus allowing for an early detection of possible future damages and economic planning of preventive remedial actions.

On the other hand we base our system on a 3D geometry model of the building. All non-geometric information concerning the building, e.g. material properties, environmental loads or inspection data, can be attached to this model. In this way an easy localization of such data is achieved, facilitating both the data collection and the estimation of the building condition for engineers involved in inspection planning, inspection or the scheduling of repair actions.

The prevalent environmental loads and material resistances vary over the whole structure and can deviate over single elements of a structure as well. A subdivision of the structure into surface areas of comparable load and resistance is necessary to gain reliable results of deterioration modelling. Therefore a hierarchic "level of detail" approach is being employed from network level down to individual hot spots on a sub-element level.

All data, geometric and non-geometric, is stored in a central relational database. This database is coupled with Java applications that serve as user interface for storing new data in the database or gaining information from it. Using the Java 3D-library, the building geometry can be presented three-dimensionally in the user interface.

Keywords: life-cycle management, 3D geometry, non-destructive inspection, reinforced concrete, deterioration mechanisms, Java, Java3D

1 Introduction

1.1 Motivation

In the last years building operators such as cities and communities as well as highway board departments become faced more and more with the problem of maintaining a stock of aging buildings with just limited funds at their disposal [1]. This has given rise to the development of Building Management Systems (BMS) and Lifecycle Management Systems (LMS). These systems offer computer-aided support for planning and realization of bridge inspections and repair work.

The basic principle of BMS and LMS is to store inspection data so that it can be reviewed at any time. Additionally in LMS this data is used to compute the building's current and future condition based on a system of condition grades.

There are two major drawbacks in most existing LMS. One is the lack of adequate deterioration models. The other is that they are based merely on data from visual inspections. In most cases the optimal time for repair measures has already passed once the deteriorations get visible at the surface. As a consequence extensive repair actions are necessary.

Predictive life-cycle management systems (PLMS) use a new approach to overcome those drawbacks. In addition to conventional visual inspections non-destructive inspection methods are used to detect deteriorations at an early stage. The future condition development of the building and its elements is computed based on fully-probabilistic deterioration models. New inspection data will lead to an update of the prognosis making it more precise. Thus a PLMS of this kind can be used to optimize the operation of bridges over their entire service life [1]. Furthermore it supports the long-term planning of inspections and repair measures as well on building as on network level.

In a current research project we are developing a software tool for the predictive life-cycle management of reinforced concrete buildings. The core of this system is a 3D building information model (BIM). All relevant data is stored in this BIM. This allows the operator of a stock of buildings easily to obtain an overview of the condition states of individual buildings in this stock. A hierarchical subdivision of structures into several levels allows a detailed allocation of information.

1.2 Related Work

Several life-cycle management systems for bridges and other reinforced concrete buildings are already in operation.

In Germany "SIB-Bauwerke" was developed by the Bundesanstalt für Straßenwesen (Federal Highway Research Institute) and now is in use on federal and federal state level [2]. The city of Düsseldorf developed another system for the maintenance planning of all bridges and tunnels within the city [3].

Examples for lifecycle management systems from other countries are KUBA-MS in Switzerland [4], DANBRO in Denmark [5], Eirspan in Ireland [6], Pontis [7] and Bridgit [8] in the USA, Ontario Bridge Management System [9] in Canada and

BridgeLife, MaintenanceMan and ServiceMan in Finland [10, 11]. Since recently in Canada “mobile model-based bridge lifecycle management systems” are being developed [12].
All of these systems can be characterized by the following properties:

- Except for the “mobile model-based bridge lifecycle management systems” [12] the geometry of the buildings is not stored.
- Adding a bridge to such a system, the bridge is structured horizontally into “parts” and vertically into levels. The number of levels differs from system to system. The smallest “part” in all these systems is a building element. A further subdivision is not used in any of these systems.
- For computing the condition prognosis of building elements or the whole building either deterministic models [e.g. 2, 5] or Markovian Chain systems [e. g. 10, 11] are used. Fully probabilistic deterioration models are not used in any of these systems.
- The condition of a building is assessed manually, based solely on visual inspection. Other non-destructive inspection methods are rarely used.

2 The Predictive Life-Cycle Management System

2.1 3D Building Model

In conventional life-cycle management systems the data concerning the building, e.g. inspection data, is allocated textually. This approach is very non-transparent and therefore error-prone as the inspection planner has to assign the data mentally to their real locations and building components.
Therefore we propose the use of a 3D building model as centre of all data acquisition and data retention activities. All non-geometric information as

- material properties,
- environmental loads,
- inspections,
- monitoring data,
- condition changes and
- repair actions

can be stored in reference to the geometry model. In addition also photos taken at inspection or files containing inspection results can be attached to the geometric model at the correct location.
This makes the allocation of information much easier and guarantees a good overview over the buildings condition. The danger of adding information to the wrong building element is minimized.
Our building information model is structured vertically into five levels of detail (LoD) as shown in Figure 1 [1]. This structure is necessary to make the optimum use of the fully-probabilistic deterioration models we are developing.

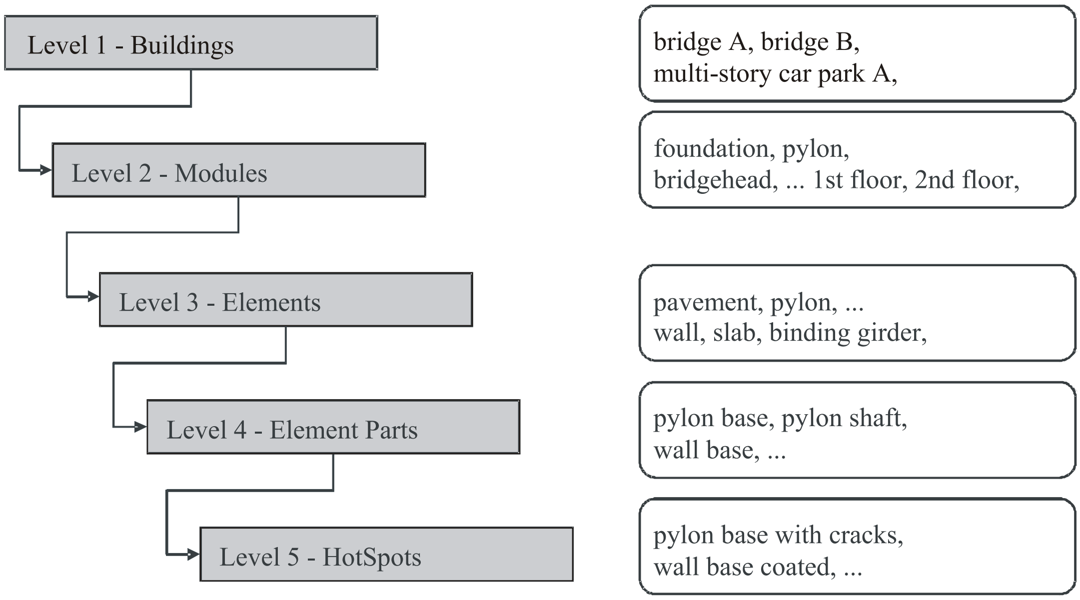


Figure 1: Hierarchical structure of the building information model [1]

The first level represents a whole building. There can be multiple entities on this level under an imaginary level 0 meaning all buildings under the administration of the public or private user of the PLMS.

The second level delineates modules. These are groups of building elements belonging together either from organizational or from functional point of view.

The building elements themselves are stored on level 3. They can be further divided in sub-element parts on level 4 and 5.

Level 4 describes element parts. These are parts of building elements that are subject of different environmental stresses than the rest of the building element. For example, wall bases under salty splash water conditions normally contain higher concentrations of chlorides than the upper wall segment. Thus the wall bases should be considered separately from the rest of the wall.

On level 5 hotspots are managed. A hotspot is a place with extraordinarily high environmental loadings and low material resistance or a place where already damage was observed. Thus a hotspot can be set by the engineer or bridge-owner during planning (e.g. jointings) or can be added later when changes in the environmental stresses or damages occur.

As the PLMS should be useable for such different infrastructural building types as bridges, parking garages, etc. the exact building structure inside those five levels can be configured by the user according to his special needs.

2.2 Architecture

The architecture of the life-cycle management system we are developing is shown in Figure 2. The system is structured in five modules grouped around a central database.

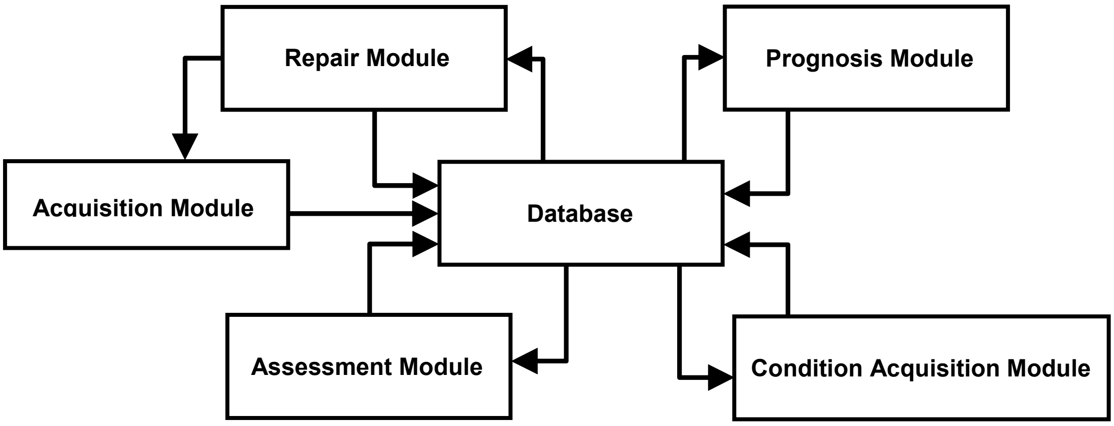


Figure 2: Architecture of the predictive life-cycle management system [1]

2.2.1 Database

The database is the core of the system. Herein, all relevant data concerning a building is stored. This comprises the geometry, all non-geometric data, the material properties, inspection data, environmental loads and so on. The geometry is stored in form of a boundary representation model (B-Rep) based on the data structure of the geometric kernel ACIS [13]. All the non-geometric data is linked to geometric features, e.g. to surfaces.

2.2.2 Acquisition Module

In the acquisition module the user can add a new building to the database. In a first step he uploads a 3D geometry constructed in an external CAD program. Inside the acquisition module he can structure the building according to the five levels mentioned before and add additional data such as material properties, construction dates, environmental loads and so on. He thereby is assisted by a three dimensional representation of the building's geometry implemented with the Java 3D library [14] as shown in Figure 3.

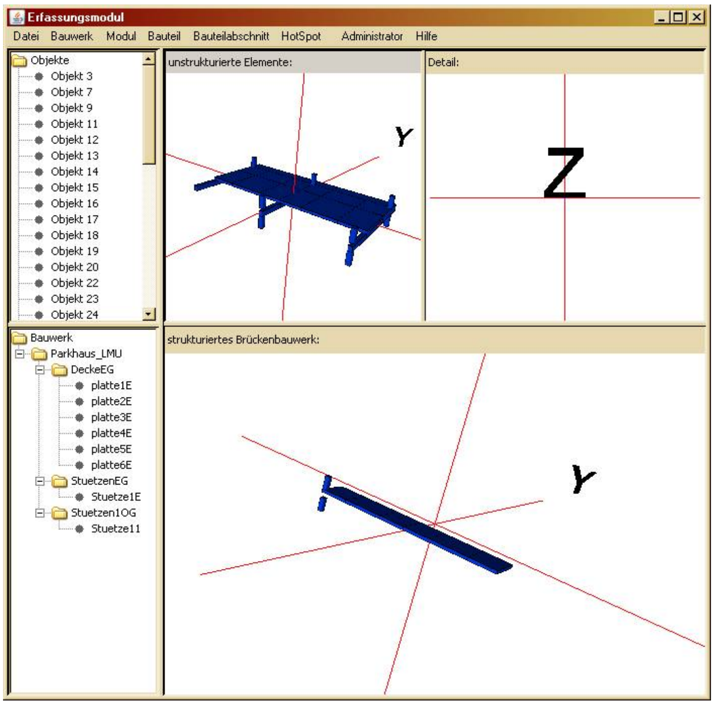
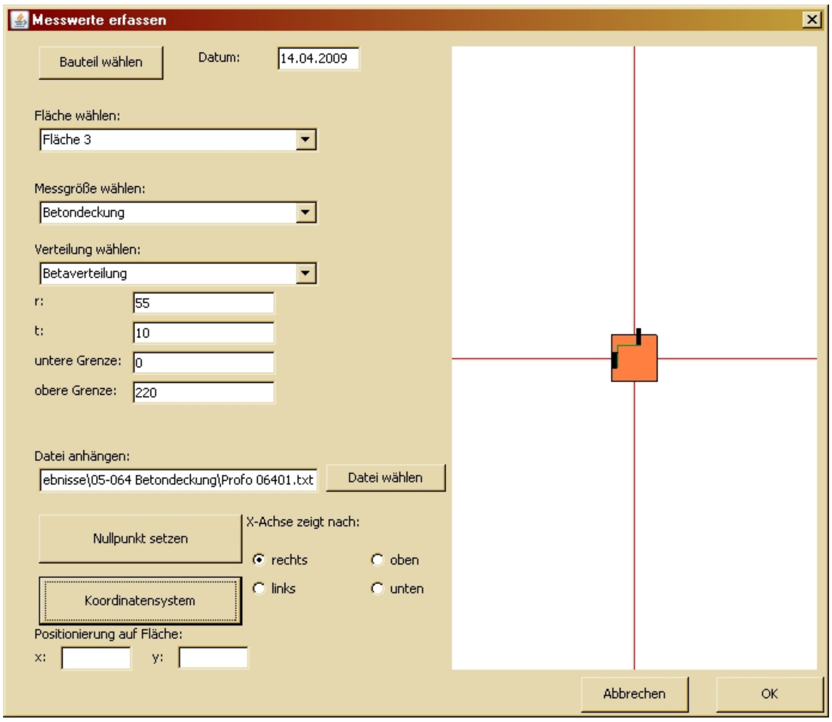


Figure 3: Graphical User Interface of the Acquisition Module

2.2.3 Condition Acquisition Module

In the condition acquisition module inspection data is added to the building information model. The inspection results are preprocessed and statistically evaluated so the user only has to enter a distribution type and the respective distribution parameters. This information will be needed for the successional prognosis computation. In addition also photos and original files created by inspection sensors can be attached to the 3D model. Similar as in the acquisition module (see Figure 3) a 3D representation of the geometry assists the correct localisation of the data.



Datum: 14.04.2009

Fläche wählen: Fläche 3

Messgröße wählen: Betondeckung

Verteilung wählen: Betaverteilung

r: 55

t: 10

untere Grenze: 0

obere Grenze: 220

Datei anhängen: ebnisse\05-064 Betondeckung\Profo 06401.txt

X-Achse zeigt nach:
● rechts ○ oben
○ links ○ unten

Positionierung auf Fläche:
x: y:

Figure 4: Graphical User Interface of the Condition Acquisition Module

2.2.4 Prognosis Module

In the prognosis module the condition prognosis over the building's lifetime is computed. Here two different cases have to be considered: For those deterioration processes for which already quantified deterioration models exist (at the moment depassivation of reinforcement due to carbonation or chloride ingress [15]) we use the software package STRUREL [16]. In all other cases we use Markovian Chains as place holders that can later be replaced by fully probabilistic deterioration models. STRUREL has originally been developed to perform probabilistic computations for problems in statics. But as the limit functions can be defined freely by the user, the program can be used for reliability studies in general.

The communication between PLMS and STRUREL is done via files. PLMS gives the deterioration model containing distribution functions for all parameters needed for the computation. STRUREL returns the condition state of the structure expressed into a structural reliability and/or a probability of failure over time (for further information see chapter 3.2). These results are stored into the database again.

By incorporation of inspection data which have been obtained from the structure with non-destructive inspection techniques (e.g. chloride profiles, carbonation depths) it is possible to specify the prior service life design.

2.2.5 Assessment Module

In the assessment module the condition state of the building is visualized. The user can choose the level of detail of the visualisation. Only the condition indices of the

lowest level (surfaces) are stored in the database, for higher levels (building elements, modules, the entire building) the condition states (e.g. reliabilities) have to be aggregated with specific algorithms (run-time based).
The smallest unit within our acquisition of structures is a single surface. For instance one surface can be one side of the six sides of a column. Therefore one element comprises several surfaces and one building comprises several elements again and so on. To generate a condition state on building level (which is called the Building Condition Index BCI), we need to have the condition states of all corresponding elements (Condition Index on element level $\mathrm{CI}_{\mathrm{element}}$).
To weight different elements to their static and safety relevance it is necessary to introduce weight-factors w, they allow a functional assessment of each type of element.
How to aggregate a condition state from surface up to element level is shown in Equation (1) wherein the $\mathrm{CI}_{\mathrm{element}}$ is displayed.

$$CI_{element} = \frac{1}{\sum_{i=1}^{n} A_i \cdot w_{e,i}} \sum_{i=1}^{n} A_i \cdot N_i \cdot w_i \tag{1}$$

A_i:	area of a single surface i	[m²]
N_i:	Condition state of surface i out of full-probabilistic deterioration modelling	[-]
$w_{e,i}$:	weight-factor for surface i	[-]

In principle, further aggregation of condition states from element level up to building level can be developed analogical, but then an amplified weighting of high Condition Indices on element level have to be considered additionally.

2.2.6 Repair Module

Whenever repair actions are taken they have to be recorded in the PLMS. This is done in the repair module. The repair module provides a catalogue of repair measures for the user to choose from. To each repair measure there is attached the expected change of condition it will cause, so if the user chooses one of them the condition data inside the database will be updated.

3 Probabilistic Deterioration Models

3.1 Process of Deterioration

Depending on exposition conditions reinforced concrete structures can be subjected to different deteriorations. For infrastructure buildings in Germany the corrosion of the reinforcement due to carbonation or chloride ingress (de-icing salts) is of particular importance (see Figure 5).

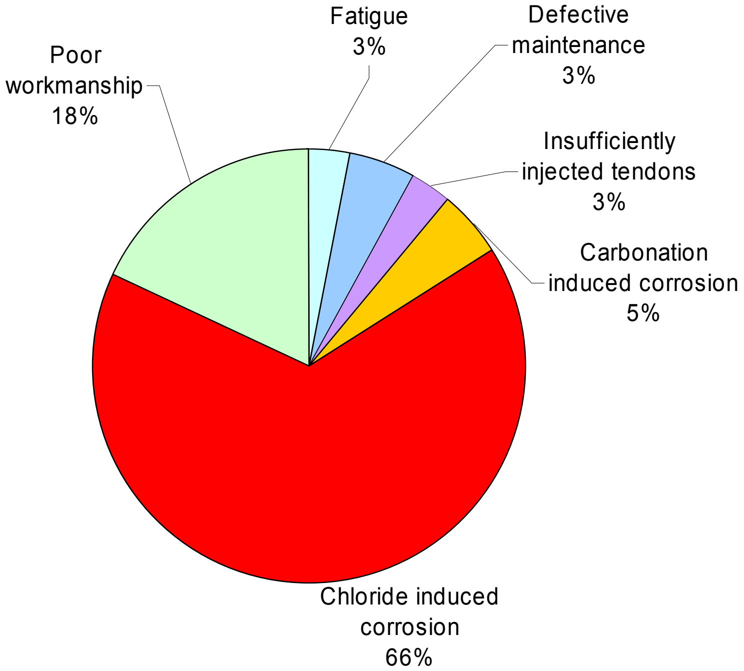


Figure 5: Frequency of failures of German bridges [1]

Normally the reinforcement in concrete is protected from corrosion by the high alkalinity of concrete’s pore solution (high pH value). A thin iron oxide layer on the surface of the steel, the so called passive layer, protects the steel. This passive layer can be destroyed either by carbonation of concrete or by ingress of chlorides. The carbonation of concrete takes place, when structures are exposed to CO_2 atmosphere and a supporting relative humidity. Carbon dioxide then reacts to calcium carbonate and decrease the pH value. The passive layer is destroyed and corrosion can occur.

Concrete structures that are exposed to de-icing salts or seawater may deteriorate from corrosion due to chloride attack. Different transport processes can be observed, e.g. diffusion, convection or dispersion. In almost all cases of chloride ingress a combination of these transport processes can be found. If a critical chloride concentration is reached at the steel surface, the steel depassivates and is disposed for corrosion.

The development in time of the relevant deterioration mechanisms of concrete structures can be modelled by a two-phase curve illustrated in Figure 6.

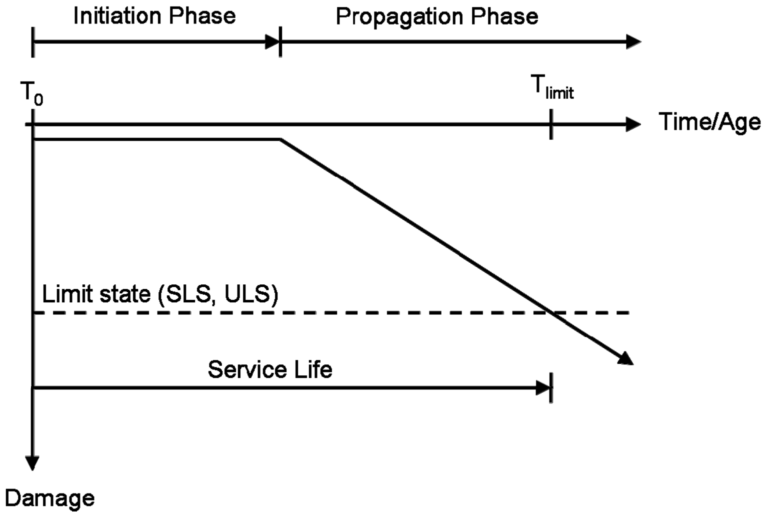


Figure 6: Service life of concrete structures. A two-phase modeling of deterioration after [17]

The process of reinforcement corrosion can be divided into two stages, the “initiation” and the “propagation” phase.

- **The initiation phase.**
  During this phase no noticeable damage of the reinforcement or the function of the structure occurs, but the passive layer is broken down by carbonation or chloride penetration. The initiation phase ends with the depassivation of the steel surface. For the initiation phase established deterioration models are available (see chapter 3.2.)

- **The propagation phase.**
  During this phase the active deterioration develops and loss of function over time is observed. Visible crack initiation and spalling of the concrete surface just occurs at a far advanced state of corrosion. At present, full probabilistic models to predict the corrosion rate are still in development.

During service life of a structure several limit states of reinforcement corrosion can be relevant for intervention. According to EC 0 [18] these states can be differentiated between serviceability limit states (SLS) and ultimate limit states (ULS). The ULS defines the loss of the load-bearing capacity (collapse of the structure), while the SLS restricts the usability or the appearance of the structure (e.g. aesthetic aspects without severe damage).

To follow an offensive strategy for the assessment of concrete structures in combination with full-probabilistic deterioration models it is obvious that the initiation phase represents the period of time where an early detection of possible future damages can be achieved. In this case cost-saving preventive remedial actions (e.g. coatings) can be taken before extensive repair actions are inevitable. The improved knowledge of the current (early identification of not visible structural weaknesses) and the future condition of the structure (e.g. by the means of non destructive testing) allows for a proper scheduling of remedial actions and budget allocation over a longer period of time.

3.2 Deterioration models

In general, design processes are based on the comparison of the resistance of the structure (R) with the applied load (S). Failure appears when the resistance is lower than the load. As the loads on a construction and the resistance are mostly variable (e.g. due to workmanship etc.), S and R cannot be compared in a deterministic way. The decision has to be based on maximum acceptable failure probabilities. The probability of failure p_f, describes the case when a variable resistance R is lower than a variable load S. This probability is required to be lower than the target probability of failure, p_{target}:

$$p_f = p\{R - S < 0\} \leq p_{target} \tag{2}$$

With the limit state function Z = R – S (R and S are distributed parameters with mean value μ and standard deviation σ) it is possible to calculate the reliability Z of the construction. If the variables S and R are normally distributed, the reliability of the construction Z itself is also normally distributed. Herein negative values define the failure probability p_f. The reliability index β describes the distance of the mean value of variable Z to the abscissa in relation to its standard deviation. Therefore, a bigger reliability yields a smaller failure probability. This safety concept is shown in Figure 7 and Equation (3).

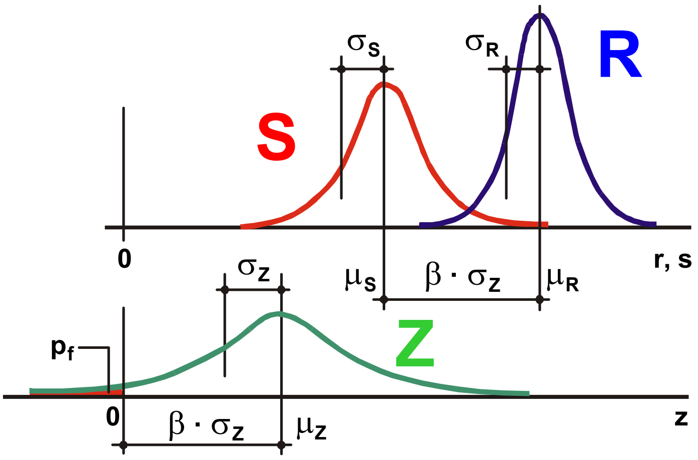


Figure 7: Safety concept for a full-probabilistic service life design

$$p_f = \int_{-\infty}^{\infty} f_s \cdot F_R \cdot dx = \Phi\left(-\frac{\mu_R - \mu_S}{\sqrt{\sigma_R^2 + \sigma_S^2}}\right) = \Phi\left(\frac{\mu_Z}{\sigma_Z}\right) = \Phi(-\beta) \tag{3}$$

Initiation period models

To calculate the carbonation depth over time the full-probabilistic design approach out of the Model Code for Service Life Design [19] can be applied, see Equation (4). With this model it is possible to predict the carbonation induced depassivation of steel in uncracked concrete.

$$x_c(t) = \sqrt{2 \cdot k_e \cdot k_c \cdot \left(k_t \cdot R_{ACC,0}^{-1} + \varepsilon_t\right) \cdot C_s} \cdot \sqrt{t} \cdot W(t) \tag{4}$$

k_e: environmental function [-]
k_c: execution transfer parameter [-]
k_t: regression parameter [-]
$R_{ACC,0}^{-1}$: inverse effective carbonation resistance [(mm²/year)/(kg/m³)]
ε_t: error term [(mm²/year)/(kg/m³)]
C_s: CO_2-concentration [kg/m³]
$W(t)$: weather function [-]

Herein, the diffusion of CO_2 is judged as the dominating transport mechanism, which is, why it is based on Fick’s first law. On the side of the material properties, the inverse carbonation resistance of the concrete $R_{ACC,0}^{-1}$ has been introduced as a decisive parameter. This material property can be obtained by using a database of several concretes or by performing a standard laboratory test which is also provided. All input parameters of the model are of stochastic nature.

For modelling the time and depth dependend chloride content, [19] recommends using Equation (5).

$$C(x,t) = \left(C_0 + \left(C_{S,\Delta x} - C_0\right) \cdot \left[1 - \operatorname{erf}\left(\frac{x - \Delta x}{2 \cdot \sqrt{D_{app,C} \cdot t}} \right) \right] \right) \tag{5}$$

C_0: initial chloride content of concrete [wt.-%/c]
$C_{S,\Delta x}$: chloride content at a depth of Δx at a certain point in time t [wt.-%/c]
x: depth with a corresponding content of chlorides $C(x,t)$ [mm]
Δx: depth of the convection zone [mm]
$D_{app,C}$: apparent coefficient of chloride diffusion through concrete [mm²/years]

This model is based on Fick’s second law of diffusion presuming that diffusion is the dominant transport mechanism. As diffusion does not cover the transport mechanisms for an intermitting chloride penetration, Fick’s second law is modified by neglecting the data until reaching the depth of the convection zone Δx and starting with a substitute surface concentration of $C_{S,\Delta x}$. This simplification allows using Equation (5) providing good accordance to in situ analyses.

It is possible to execute an update of a prior service life design by the means of inspection data e.g. carbonation depth or chloride profiles at the time t (mentioned before in chapter 2.2.4). The so-called Bayesian Update can be accomplished by drafting boundary conditions which take the inspection data into account. If new inspection data is available such a procedure is always recommended, as uncertainties can be cut down.

The different deterioration models give the limit functions for the probabilistic computation in STRUREL. In PLMS the user can choose for which type of deterioration, carbonation or chloride ingress, he wants to compute the prognosis, and if this is the initial prognosis or an update. The relevant limit function as well as the needed parameters then are written into an input file for STRUREL which then performs the probabilistic prognosis computation.

4 Summary

In a current research project we are developing a software tool for the predictive life-cycle management of reinforced concrete buildings. A key feature of our system is a 3D building information model which forms the basis of all data acquisition and evaluation functionality. This model serves to store all non-geometric information on building elements in relation to their geometry. The model provides multiple levels of detail and means to associate semantic classes with geometric objects. As the life-cycle management system is designed for different kinds of building types an explicitly available meta-model has been integrated which is used to generate a specific building information model.

In contrast to other existing building management systems in our tool the building is structured into five levels of detail. The structures are divided into modules and further into building elements. There are also sub-element levels of element parts and so called “hot spots”. The advantage of this approach is that information like for example inspection results or photos can be located exactly inside the geometry. The subdivision is necessary to make use of full probabilistic deterioration models.

These full probabilistic deterioration models are used to compute the future condition states of the whole building or its individual parts. Therefore they are combined with non-destructive inspection methods that offer a more precise prognosis of the future condition especially in the initiation phase of reinforcement corrosion (update of the prior service life design). The condition prognosis is done for the surfaces on the lowest level and can be aggregated to compute the condition state of whole modules or the entire building.

In this way deteriorations can be detected at an early stage and preventive repair measures can be planned to keep the corrosion process under control. This consequently means a reduction of the financial outlay for the structure’s maintenance.

By the use of a 3D model non-geometric information can be easily allocated to the building by the user. Also the condition states of the building and its individual elements can be visualized with the 3D model.

Acknowledgements

The presented project is sponsored by the Bundesministerium für Bildung und Forschung (BMBF) within the research framework "Building sustainably with concrete".

References

[1] P. Schießl, , T.F. Mayer, „Schlussberichte zur ersten Phase des DAfStb/BMBF-Verbundforschungsvorhabens "Nachhaltig Bauen mit Beton". Deutscher Ausschuss für Stahlbeton Heft 572", Beuth-Verlag, Berlin, Germany, 2007.
[2] P. Haardt, "Entwicklung eines Bauwerks-Management-Systems für das deutsche Fernstraßennetz, Stufe 1 und 2, Schlussbericht zum AP-Projekt 99 245", Bundesanstalt für das Straßenwesen, Bergisch-Gladbach, Germany, 2002.
[3] Landeshauptstadt Düsseldorf, "Lebensdauermanagement für Ingenieurbauwerke der Landeshauptstadt Düsseldorf", Homepage (http://www.duesseldorf.de/verkehrsmanagement/bruecken_und_tunnel/index.sthtml), Düsseldorf, Germany, 2009.
[4] H. Haller, G. Bascuro, "KUBA-DB Benutzerhandbuch", Eidg. Drucksachen- und Materialzentrale, Bern, Switzerland, 2006.
[5] A. Henriksen, "Bridge Management – Routine Maintenance: Recent Experience with the Routine Management Module in the DANBRO Bridge Management System" in "Proceedings of the 8th International Bridge Management Conference", Transportation Research Board, Denver, Colorado, I-5/1-13, 1999.
[6] L. Duffy, "Development of Eirspan: Ireland's Bridge Management System", Institution of Civil Engineers, London, United Kingdom, 2004.
[7] W. Robert, A. Marshall, R. Shepard, J. Aldayuz, "Pontis Bridge Management System – State of Practice in Implementation and Development" in "Proceedings of the 9th International Bridge Management Conference", Transportation Research Board, Orlando, Florida, 2003.
[8] H. Hawk, "BRIDGIT: User-Friendly Approach to Bridge-Management" in "Proceedings of the 8th International Bridge Management Conference", Transportation Research Board, Denver, Colorado, E-7/1-15, 1999.
[9] P. Thompson, T. Merlo, B. Kerr, A. Cheetham, R. Ellis, "The New Ontario Bridge Management System" in "Proceedings of the 8th International Bridge Management Conference", Transportation Research Board, Denver, Colorado, F-6/1-15, 1999.
[10] E. Vesikari, "BRIDGELIFE, User Manual", VTT, Helsinki, Finland, 2006.
[11] E. Vesikari, "Life-Cycle Management Tools for Civil Infrastructure", Proc. 3rd Int. Workshop on Lifetime Engineering of Civil Infrastructure, Yamaguchi University, Japan, 2008.
[12] A. Hammad, C. Zhang, Y. Hu, "Mobile Model-Based Bridge Lifecycle

Management Systems", Computer-Aided Civil and Infrastructure Engineering, 21, 530 -547, 2006.

[13] Spatial, "Documentation of 3D ACIS Modeler", Spatial, Westminster, Colorado, 2006.

[14] Sun Microsystems, "Documentation of Java3D Ed 1.5.0", Sun Microsystems, Santa Clara, California, 2006.

[15] C. Gehlen, "Probabilistische Lebensdauerbemessung von Stahlbetonbauwerken – Zuverlässigkeitsbetrachtungen zur wirksamen Vermeidung von Bewehrungskorrosion", Deutscher Ausschuss für Stahlbetonbau (DAfStB), Berlin, Germany, 2000.

[16] RCP, "Documentation of STRUREL", RCP, Munich, Germany, 2007.

[17] K. Tuutti, "Corrosion of Steel in Concrete", CBI Research, No. Fo 4:82, Swedish Cement and Concrete Research Institute, Sweden, Stockholm, 1982.

[18] Eurocode 0, EN1990, Basis of structural design, 2001.

[19] P. Schießl, et al., "Model Code for Service Life Design", fib bulletin 34, Lausanne, Switzerland, 2006.