Decision-making for the efficient life cycle management of structures

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Abstract
Structures made of structural concrete are designed to withstand different time-dependent or time-independent influences during their expected service lifetime. Most of these influences can be considered in a sufficient manner by mathematical and statistical approaches, while some do appear combined with certain structural, environmental, and material boundary conditions. These can, in most cases, not be foreseen, verified or they change during the lifecycle of a concrete structure. It is therefore obligatory to rely on an efficient conservation strategy for each structure to ensure its safety and overall economic efficiency. For this purpose, the fib Model Code for Concrete Structures 2010 already suggests a general workflow to follow a predefined or provisional conservation strategy and condition control procedure. These existing proposals are yet of very general nature and disclaim practical decision-making rules to survey and assess existing structures as part of a condition-based conservation strategy. In this contribution, the main decision-making options at an early stage of a construction's life cycle management are pointed out, considering their importance for a structure's time-dependent performance and their relation to continuative decisions for conservation management. Proposals for the implementation of practical advice for condition-based conservation strategies in international guidelines are made.

KEYWORDS
assessment, conservation, decision-making, inspection, life cycle management

1 | INTRODUCTION
The life cycle of a concrete structure can be divided into four essential stages:

- Design (in case of a new structure) and redesign (assessment of an existing structure) stage.
- The stage of construction.
- Usage of the structure, closely combined with its conservation.
- Dismantlement of the structure.

During the stage of usage (3), which engages the major period along a structure's life cycle, different performance...
requirements do permanently and verifiably have to be fulfilled. Performance in this context is defined as the compliance with demands on the structural performance (bearing capacity in the context of ultimate limit state and serviceability limit state verification, considering predictable load situations), durability, economic efficiency, appearance of a structure in use and others. To permanently guarantee conformity with these requirements, several decisions have to be made along the service life of a construction. Decisions at the beginning of the life cycle (design or redesign stage) affect the structure’s overall performance in a particular manner, as it will be explained in Section 2. Furthermore, these early decisions do have a strong influence on nearly each continuative decision, especially the conservation strategy, as it will be shown in Section 3.

Figure 1 expresses the assignment of main and secondary decision-making options alongside the life cycle management (LCM) of a structure to the essential stages of its life cycle, as they were stated above. Figure 1 furthermore displays the necessity of decision-making in the design/redesign stage and the influence such decisions have in the overall sense of a LCM.

2 | PRIMARY DECISION-MAKING

2.1 | General

At the beginning of a design or, concerning existing buildings, assessment process, labeled LCM Stage 1 (see Figure 1), it is obligatory to make primary decisions about a construction, concerning:

- The expected (residual) service life.
- The target reliability index.
- Possible/expected deterioration mechanisms of the structure or parts of it.
- Consequences in case of failure.

The current, internationally introduced design principles and rules, such as the Eurocodes or the *fib* Model Code 2010, offer proposals for optimal decision-making about new to be build structures (design stage). Making the same decisions about existing structures (assessment stage) is a far more complex activity, demanding further studies, data input from condition assessment procedures and the execution of probabilistic calculations. Both statements will be explained in this section. The expected influence of each decision on secondary steps of decision-making will be highlighted in Section 3.1

2.2 | Service life

2.2.1 | Design service life for new constructions

The design service life of a new construction is defined as the period between construction and the end of use. All
performance requirements have to be satisfied during this period.

By respecting internationally harmonized principles of structural design (see EN 1990 or EN 1992), a service life according to Table 1 can be presumed for new constructions.

### 2.2.2 Residual service life of existing structures

The residual service life of an existing structure is defined as the period between its assessment/condition evaluation and its end of use. All performance requirements have to be satisfied during this period.

The residual service life has to be defined using the outcome of an integral assessment process. Information about the resistance of structural parts against deterioration/damage mechanisms (e.g., concrete cover rate, resistance against fatigue) has to be evaluated together with the yet emerged deterioration rate (see Section 3). The gathered data then should be outweighed against all future predicted damage mechanisms and loads. A calculatory prediction of future deterioration may be performed using various methods, such as:

- Structural analysis: Evaluation of the load bearing capacity of current or future deteriorated members and material/cross-sectional resistance against fatigue.
- Empirical prediction models for concrete and steel degradation: frost–thaw damage and carbonization of concrete, chloride-ion ingress in concrete cover shell and corrosion of reinforcement/prestressing members (see Prammer).
- Probabilistic calculation of input parameters for empirical prediction models (see^2).

Predicting the residual service life of a structure, one has to take account of the fact, that existing buildings might have been build using older technical standards.

### 2.3 Target reliability

#### 2.3.1 General

The reliability of a structural component is generally measured by its reliability index \( \beta \) and described by the following equation with \( P_f \) as the failure probability in a chosen reference time period and \( \theta \) as the function of the standard normal distribution of a failure mode:

\[
\beta = -\theta^{-1}(P_f)
\]

In structural design according to international standards like the Eurocodes, the defined failure mode is the exceedance of an action over a material resistance parameter, which describes the limit state design rules. The relation between the reliability index \( \beta \) and the failure probability \( P_f \) in a reference period of 1 year can be summarized as shown in Table 2. For choosing an appropriate reliability index, well-founded reliability calculations have to be executed, considering defined or expected boundary conditions, like the (residual) service life (see Section 2.2), consequences of failure or cost of safety measures.

#### 2.3.2 Target reliability index for new structures

Concerning the design of new concrete structures, a practical engineer does not have to consider reliability calculations in most cases. By applying the deterministic safety approach of DIN EN 1990 (partial factor method), the following recommended target reliability indices for a reference period of 50 years’ service life are mathematically reached:

- \( \beta = 1.5 \) for serviceability limit states verification (SLS).

| TABLE 1 | Specified (design) service life

| Type of structure | Specified (design) service life |
|-------------------|--------------------------------|
| Temporary structures | 1–5 years |
| Replaceable components of structures | 25 years |
| Examples: gantry girders, bearings, expansion joints, bridge caps |
| Buildings and other common structures of average importance | 50 years |
| Structures of greater importance | 100 years or more |
| Examples: monumental buildings, large bridges, other special, or important structures |

| TABLE 2 | Failure probability and reliability index for a 1-year reference period |
|---------|----------------|
| \( P_f \) | \( 10^{-1} \) | \( 10^{-2} \) | \( 10^{-3} \) | \( 10^{-4} \) | \( 10^{-5} \) | \( 10^{-6} \) | \( 10^{-7} \) |
| \( \beta \) | 1.3 | 2.3 | 3.1 | 3.7 | 4.2 | 4.7 | 5.2 |
• \( \beta = 3.1 \) for fatigue verification.
• \( \beta = 3.8 \) for ultimate limit states verification (ULS).

The suggested reliability indices apply to individual parts of a construction (component reliability with one dominant failure mode). According to the system of a structure assembled by different components, the practical engineer has to ensure that the probability of a system failure is not exceeded. This is performed through the robustness requirements.5

2.3.3 | Reliability index of existing structures

Since many existing structures were built in accordance with yet redeemed national codes, their actual reliability index deviates from the assumptions for new constructions. Furthermore, a potentially deteriorated construction may have a lower reliability, depending on the impact of the occurred damage.

The easiest but as well imprecise (on the safe side) way to ensure a sufficient reliability index of existing structures has been introduced by guidelines in different countries of Europe. By a static recalculation in accordance to currently in use codes, that is, the appliance of the deterministic partial safety factor approach on existing structures, it is possible to validate the commonly (for new structures) presupposed reliability indices as shown in the foregoing section.3,6 It has to be mentioned, that differences between old and new technical design rules, like for example the minimum concrete cover rate, may exist. These differences have to be rated as well for reliability analyses, together with the evaluation of structural damages which may have occurred yet.

A more precise validation method has been proposed by the fib task group 3.1 in the fib Bulletin 80. The so-called adjusted partial factor method allows for the determination of more realistic partial factors under consideration of lower reliability demands on older structures with a shorter residual lifetime. These adjusted partial factors can be derived for the material resistances as well as for constant and variable load situations.7

Another way of proving sufficient reliability of an existing structure, are reliability analyses, that is, the calculation of the actual reliability of a structure regarding significant boundary condition, like the residual service life (see Section 2.2), the condition of the building materials and their real mechanical properties or the effective load situations. The main reliability analyses principles are, according to JCSS4:

- **Component reliability analysis**: Computation of the existing reliability index and failure probability of a structures member by analyzing appropriate limit state functions, basic variables, and time reference; following sensitivity studies.
- **System reliability analysis**: Connecting reliability analysis of components in series/parallel systems.
- **Time-dependent reliability analysis**: Regarding time dependency in resistance and influence analysis.

According to fib Model Code 2010, the target reliability of an existing structure can be chosen in a range as shown in Table 3.1 In comparison to new constructions, higher relative costs of safety measures to raise the reliability legitimate a lower target reliability index.4

2.4 | Consequences of failure

The failure of a structure or structural part leads to different consequences in terms of risk to life, injury, cultural damage, economical loss, and/or environmental damage. The knowledge of these possible consequences is of high interest for the calculation of a construction’s reliability in its design or assessment process. So-called Consequences Classes (CC) according to Table 4 were introduced in international standards for the classification of structures, regarding its ratio \( \rho \) between total costs in case of failure and construction costs.1,4,8

The classification of a structure into a CC is a non-trivial task for an engineer, due to the necessity of estimating property damage costs or costs for a possible injury of persons or loss of life. Consequences of failure do furthermore depend on the failure mode of the structure.

| Limit states | Target reliability index | Reference period |
|--------------|--------------------------|------------------|
| Serviceability | 1.5 | Residual service life |
| Ultimate     | In the range of 3.1–3.8a | 50 years         |
|              | In the range of 3.4–4.1a | 15 years         |
|              | In the range of 4.1–4.7a | 1 year           |

aDepending on the costs of safety measures for upgrading the existing structure.

| CC   | \( \rho \) | Classification  |
|------|---------|----------------|
| 1    | <2      | Minor consequences |
| 2    | 2–5     | Moderate consequences |
| 3    | 5–10    | Large consequences  |
| —    | >10     | Extreme consequences |

TABLE 3 | Target reliability indices for existing structures4

TABLE 4 | Definition of consequences classes4
The failure mechanisms of robust constructions, such as redundant bearing elements with failure announcement (ductile failure), might, for example, more likely lead to material damage costs than costs for loss of life. Expected brittle failure modes may therefore lead to higher consequences. The static robustness of a structure should be examined during the design phase of structures for each structural component by the planning engineer.

Consequences of failure, leading to material damage, can be calculated by a cost estimation for repair and strengthening interventions, in the worst case for the cost of complete reconstruction. For the calculation of costs, consequences due to damage to life or even death might be estimated by referring to statistical evaluations for different scenarios. For example, the federal German highway institute BASt regularly publishes monetary stated costs for injury and death on German highways due to car accidents. Examples are given in Table 5.

It has to be mentioned that there is still a need for approximating the number of possibly involved persons in an accident. This approximation might be done by a statistical approach using data of car crossings (in case of a road bridge) or attendance numbers for buildings. Table 6 gives a (noncomplete) proposal for a generalized Consequences-Class classification, regarding the type of structure, as it is introduced in the German VDI-Richtlinie 6200. Giving an example, the total collapse of a main road bridge may lead to costs of 35 Million Euro for reconstruction, 20 Million Euro for personal and material damage (injury or death) and 30 Million Euro of economic costs. If the existing bridge before the collapse had a worth of around 15 Million Euro, it might be labeled to CC 3 (high consequences).

### 2.5 Deterioration of concrete structures

#### 2.5.1 General

On the one hand, the actual state-of-the-art technical design principles and rules for structures made out of reinforced concrete, like the currently available Eurocodes and the fib Model Code 2010, offer mathematical approaches to ensure that effects on a structure and resistances of material are in

| **Severity** | **Type of damage/consequences** | **Material damage (€)** | **Injury or death (€)** |
|--------------|---------------------------------|------------------------|------------------------|
| Car accident with light injuries | 15,405 | 5,138 |
| Car accident with heavy injuries | 23,994 | 116,335 |
| Car accident leading to death | 51,322 | 1,150,234 |

**TABLE 5** Monetary consequences of car accidents on German highways in 2017

| **CC** | **Description** | **Examples: buildings** | **Examples: infrastructure** |
|--------|-----------------|------------------------|-----------------------------|
| 1      | Damage to life and health for a lot of persons, major environmental damage | Theaters, hospitals, high rise buildings, stadiums, congress halls, multipurpose arenas | Road and railway bridges, supporting walls, noise barriers, and traffic sign bridges on main roads |
| 2      | Damage to life and health for many persons, serious environmental damage | Television towers, office buildings, industrial buildings, apartment buildings, power stations, production plants, train stations, airport buildings, shopping malls, museums, theatres, schools | Road and railway bridges, supporting walls, noise barriers, and traffic sign bridges on minor roads |
| 3      | Material damage and financial loss, low environmental damage, risk to individual persons | Agricultural structures, silos, masts, detached residential houses, apartments | Objects of infrastructure without public access |

**TABLE 6** CC and examples for classification according to Reference

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Abbreviation: CC, Consequences Classes.
accordance with the expected reliability of a structure during the chosen reference period, as mentioned in the last sections. These approaches are generally well founded in terms of scientific research outcome and the likelihood of unexpected change in these assumptions during a construction's service life is low. Theoretically, the structural condition should agree with the performance requirements, which accompany the primary decisions.

Possible time-dependent effects on a structure, like for example, traffic or exceptional loads, are on the other hand constrained statistically in terms of a future prediction. Time-dependent material degradation processes are considered only in an implicit mathematical way, for example by defining minimal concrete cover rates with respect to expected environmental and or mechanical exposure. However, these aforementioned time-dependent processes are in many cases of a not fully predictable, or mathematically describable nature and may in addition change during a structure's service lifetime.¹

For this reason, each structural part should be evaluated concerning possible deterioration mechanisms, which might not have been, implicitly or directly, taken account of during the design process. The outcome of this evaluation offers an insight and the fundamentals for further decision-making steps for an effective LCM. Following, the most necessary evaluations are mentioned.

### 2.5.2 Fatigue performance of structures and materials

Fatigue design is an essential part of the verification of structural safety in the ultimate limit state of reinforced and prestressed concrete structures. This verification has to be carried out once a structure is expected to be exposed to loads which cannot be verified as static or quasi-static anymore or which are of dynamic nature. Examples are axial loads from road traffic, induced vibrational loads from machine basements, frequent temperature induced restraining forces and others. In fatigue design, the planning engineer compares these loads, respectively the induced stress range, with the resistance of the evaluated cross section/material. This resistance is influenced by the induced stress cycles over time and the heightness of the maximum and minimum stresses.¹

During the design phase of new structures, the fatigue-relevant loads must be determined to guarantee the structural safety and reliability during the whole chosen service life of a construction (see primary decision-making, Section 2). For this purpose, a good prediction or estimation of future loads, possibly time varying, is essential, considering the following questions:

- Will the load assumption hold for the chosen service lifetime?
- Will fatigue-relevant loads appear, which are not respected in the structural design?

Concerning the assessment of existing structures, the following, far more complex questions must additionally be examined:

- Which fatigue relevant loads did appear in which time period of the structure's service life?
- Which fatigue damage did appear to date (assessment point) in the construction?

### 2.5.3 Durability-related exposure

The exposure of a construction, or parts of it, to detrimental environmental conditions may lead to time-dependent deterioration mechanisms like corrosion of reinforcement bars/prestressing members or the concrete cross sections. To avoid or reduce the effect of these, in most cases unavoidable, environmental conditions, the planning engineer must make decisions about:

- The composition and strength of the chosen concrete material.
- The thickness of the concrete layer surrounding the steel members.
- The chemical composition of steel members.
- The optimal protection system for prestressing members.

| Exposure categories                      | Environmental conditions                      |
|-----------------------------------------|---------------------------------------------|
| No risk of corrosion or attack          | Exposure to very dry environment             |
| Corrosion induced by carbonation        | Exposure to air and moisture                 |
| Corrosion induced by chlorides other than from seawater | Exposure to deicing agents or airborne chlorides |
| Corrosion induced by chlorides from seawater | Exposure to seawater                       |
| Freezing and thawing attack             | Exposure to moisture and freeze–thaw cycles |
| Chemical attack                         | Exposure to aggressive chemical environment, e.g., components (gas, liquid, or solid) or aggressive industrial atmosphere |
The necessity of additional protection measures (coating, impregnation).

As mentioned above, national and international technical guidelines do already give proposals for these decisions, referring to so-called exposure classes, presented in Table 7. These are chosen in the design stage to (theoretically) guaranty an adequate durability of the structure during the chosen service lifetime. The proposals are directly linked to decisions made about the necessary concrete quality and layer thickness. Although these prescribed decisions are well founded, a direct connection to elementary boundary conditions of the environmental exposure (e.g., the strength of the ion-chloride ingress) is missing. As a consequence, the planning engineer must make additional decisions:

- Do the proposals of guidelines fit for the whole construction or parts of it?
- Will increased detrimental exposure occur locally? (e.g., chloride-ion ingress above the main lane of a highway, processed with deicing agents).
- May changes in the assumptions of environmental exposure appear during the service lifetime?

Concerning the assessment of existing structures, the following, far more complex questions must additionally be examined.

- Which timely varying detrimental exposure did appear to date (assessment point) in the construction?

3 | SECONDARY DECISION-MAKING

3.1 | General

The following necessary decisions about a concrete structure were illustrated in the previous section and are necessary to be made at the very beginning of an LCM:

- Decisions about the expected (residual) service life.
- Decisions about the target reliability of a structure.
- Decisions about/evaluation of the consequences of failure.
- Decisions about/evaluation of the main deterioration mechanisms.

These decisions were labeled as primary since they influence various subsequent decisions along the LCM of a structure. As depicted in Figure 1, one will come across further decisions to be made during the whole service lifetime of a structure, including its start and end point. The conjunction of these, so-called secondary decisions, with the primary ones is shortly discussed in the following sections. It has to be mentioned, that further decisions might have to be made, regarding individual conditions. The noncompleteness of the following exemplifications must therefore be stated.

3.2 | Construction

At the design stage, the target reliability of a construction has to be evaluated, as explained in Section 2. Before the construction process can be initiated (Stage 2 of the LCM, see Picture 1) the extent of the collateral and individual quality management measures has to be defined among the contractors. These decisions have to be made under reference to the aimed reliability of a structure as well as its planned service life, as shown in Table 8.

The chosen class of quality management has a high influence on the verifiable requirements on the construction company, the depth of supervision during construction (quality of construction works, quality of the building materials), the technical documentation during construction and the quality plan, containing the organization of workflows, staff assignment and others. Further information is given in DIN.

3.3 | Conservation

3.3.1 | General

Deterioration mechanisms, as they were briefly introduced in Section 2.5, directly affect a structure's

| Table 8 | Quality management in construction stage |
|---------|----------------------------------------|
| QM class | Target reliability index β | Reference period: 1 year | Reference period: 50 years | Quality management in construction |
| 1       | 4.2 | 3.3 | Regular control depth: Self-supervision |
| 2       | 4.7 | 3.8 | Regular control depth: Supervision by inspection agency from contractor |
| 3       | 5.2 | 4.3 | Increased control depth: Supervision by an independent inspection agency |
reliability. For this reason, there is an obvious need for verification of the assumptions taken during the design or assessment process of a structure. One possible way of verification might be in a direct manner, for example by evaluating the actual load situations in different time periods or the ingress of carbon dioxide into the concrete cover over time. This kind of verification process allows the implementation of a proactive conservation strategy, that is, predict the approximate future behavior of a structure (e.g., a potential reduction of its reliability) and make further decisions about necessary interventions. The effort and costs of this proactive conservation strategy can become very high with dependency to the amount of boundary conditions surveyed and data to be collected and evaluated. The question arises, if international standards should give deeper proposals for the usage of this type of service life verification and conservation strategy or more practical and economical feasible advice should be given. This possible option is the execution of a condition-based conservation strategy, as for example proposed in fib Model Code 2010. Applying a condition-based conservation strategy on a construction means, that the actual state of the structure itself is examined and compared to a defined reference state. As soon as chosen threshold levels of damage are exceeded, the decision-making processes for intervention can be performed.

The reference state of a structure can be defined by condition assessment procedures, shortly described in the following section.

A continuous/periodic survey by inspections will provide the basis for a condition-based conservation method. The development of different national guidelines and codes, for example, the VDI-Richtlinie 6200 and the DIN 1076 (Germany) or the RVS (Austria), which build the basis of ensuring safe structures in these countries, gives hints, that deeper proposals on how and when to execute these inspections are necessary.

A first proposal for inspection intervals and their reference to the primary decision-making options is given in the following sections.

### 3.3.2 | Condition assessment

An efficient conservation management of existing structures can be performed only provided that its present condition is known. To acquire knowledge about the existing structure, the following condition assessment options may be decided and executed:

- Testing of material parameters.
- Verification of the load assumptions.
- Initial (thorough) inspection and damage/deterioration examination.
- Performance testing (e.g., proof loading combined with measurement methods).
- Structural evaluation/assessment with different levels of refinement and the possibility of system identification by proof loading.

| TABLE 9 | Proposal for periodic inspection intervals according to Reference 8 |
| --- | --- | --- |
| CC | Surveillance | Inspection | Thorough examination |
| 3 | 3–5 years | As required | |
| 2 | 2–3 years | 4–5 years | 12–15 years |
| 1 | 1–2 years | 2–3 years | 6–9 years |

Abbreviation: CC, Consequences Classes.

| TABLE 10 | Decision-making for dismantlement |
| --- | --- |
| **Primary decision-making (correlation)** | **Secondary decision-making for dismantlement** |
| Service life, reliability index | Point of dismantlement | For reasons of safety, the dismantlement procedure must be executed before the service life is exceeded (i.e., the remaining lifting capacity for the dismantlement methods) |
| Consequences of failure, fatigue performance | Dismantlement methods, safety requirements | The definition of consequences of failure includes the evaluation of critical points in the structure, as well as possible redundancies. This information must be considered while selecting appropriate dismantlement methods as well as safety measures during dismantlement |
| Durability-related deterioration | Measures for protection of the environment | The evaluated durability-related deterioration mechanisms provide information about a possible contamination of building materials. This information must be considered in the waste management concept during dismantlement |
3.3.3 | Condition survey

For defining periodic inspection intervals as part of a conservation strategy, it is proposed to offer the practical engineer, as well as a yet existing building’s owner, a practically feasible decision-making option. Table 9 shows a proposal for implementing possible ranges of periodic inspection intervals for structures into international standards, relegating to the CC classification according to Section 2.4. The given periods are extracted from VDI-Richtlinie 6200, since they best summarize yet successfully applied national guidelines and codes.\(^6,8,11,12\)

The terms “Surveillance,” “Inspection,” and “Thorough examination” are further defined in the VDI-Richtlinie, which is also available in English. Information about the depth of these different inspections and requirements to the executing staff are given there.\(^8\)

3.4 | Dismantlement

The primary decisions made about new and existing structures may influence the dismantlement procedure as the last LCM activity at the end of service life. Secondary decisions for dismantlement procedures should especially include considerations about the safety of the structure and its surrounding environment, as well as explicit environmental hazard. Methods for dismantlement must be concerted to the given constraints. Table 10 gives a brief overview of these decisions and their correlation to the primary decisions, as stated in Section 2.

4 | CONCLUSIONS

At the very beginning of a concrete structure’s LCM (design stage, or concerning existing structures, assessment stage), primary decisions should be made by the owner of the structure and the planning engineers. These main decisions are: Definition of the (residual) expected service life, decision about/evaluation of the target reliability of a construction, evaluation of consequences of failure and of decisive deterioration mechanisms acting on the structure. This decision-making process must consider a possible change in usage (e.g., loads, environmental exposure) of an existing structure.

Further (secondary) decisions govern the whole LCM and are directly influenced by the primary decisions that were made. In this contribution, some of these secondary decision-making options are pointed out. During construction stage, the target reliability of a construction is an indicator for the necessary depth of quality management. In a reactive or proactive conservation management, it is important to regularly survey the condition of structures, respectively, the assumption made during design/redesign stage. Information is provided on how proposed intervals of inspection are linked to the consequences in case of failure of a structure. At the last stage of LCM, primary decision/evaluations made at the very beginning of the service life do influence the dismantlement procedure, ranging from dismantlement methods to the chosen waste management concept.

5 | OUTLOOK

The identification of further decisive decision-making options for an effective LCM of both existing and new structures should be a relevant contribution to international codes and guidelines, not least due to the high amount of existing structures. The following topics shall be treated in further research:

- Locations for surveys and monitoring activities.
- Tools and techniques for condition survey (e.g., monitoring options).
- Elaboration of guidelines for the identification of critical constructional parts and redundancies (robustness criteria).
- Elaboration of an extended consequences of failure table for different types of construction, taking into account simple cases of failure mechanisms and related damage accumulation.
- Proposals for a deeper treatment of special conditions for deterioration, added to the international guidelines.
- Elaboration of technical methods to easily (roughly) estimate the residual service life of structures without refined calculations.
- Decision-making options for intervention and the definition of threshold levels as required for such decisions.

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REFERENCES

1. fib. fib Model Code for concrete structures. Lausanne, Switzerland: Fédération Internationale du Béton (fib), 2013.
2. Bergmeister K, Fingerloos F, Wörner J-D. Lebensdauorientierter Entwurf, Konstruktion, Nachrechnung. Beton Kalender 2013, Lebensdauer und Instandsetzung, Brandschutz. Berlin: Ernst & Sohn, 2013.
3. Prammer D. Life-cycle management of concrete structures [PhD]. Vienna, Austria: AIT Austrian Institute of Technology GmbH, University of Natural Resources and Life Sciences; 2018.
4. JCSS. Probabilistic Model Code. Lyngby, Denmark: Joint Committee on Structural Safety, 2001.
5. CEN. EN 1990 Eurocode: Basis of structural design. Brussels, Belgium: European Committee for Standardization, 2010.
6. Zimmert F, Braml T. Decision-making about and management of structures—Status quo and outlook. Proc fib Symp. 2019; 2019:1419–1426.
7. fib. fib Bulletin 80—Partial factor methods for existing concrete structures. Lausanne, Switzerland: Fédération Internationale du Béton (fib), 2016.
8. VDI. VDI-Richtlinien, VDI 6200 – Standsicherheit von Bauwerken, Regelmäßige Überprüfung – Structural safety of buildings, Regular inspections. Düsseldorf, Germany: Verein Deutscher Ingenieure e.V., 2010.
9. BASI. Volkswirtschaftliche Kosten von Straßenverkehrsunfällen in Deutschland. 2019 [cited 2019 Feb 7]; Available from: https://www.basi.de/BASI_2017/DE/Statistik/Unfaelle/volkswirtschaftliche_kosten.pdf?blob=publicationFile&v=13
10. DIN. DIN EN 13670 – Ausführung von Tragwerken aus Beton; Deutsche Fassung EN 13670:2009. Normenausschuss Bauwesen (NABau) im DIN Deutsches Institut für Normung e.V., Berlin, Germany; 2011.
11. DIN. DIN 1076 – Ingenieurbauwerke im Zuge von Straßen und Wegen, Überwachung und Prüfung. Normenausschuss Bauwesen (NABau) im DIN Deutsches Institut für Normung e. V., Berlin, Germany; 1999.
12. BMVT. Neue Richtlinien für die Prüfung und das Monitoring von Brücken. Bundesministerium für Verkehr, Innovation und Technologie, Wien, Austria; 2011.

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