

DURABILITY DESIGN OF CONCRETE STRUCTURES - PART 1: ANALYSIS FUNDAMENTALS

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Abstract. *Concrete structures (CS) are designed so that they can satisfy requirements regarding safety, serviceability, durability and aesthetics throughout their design service life. Present design procedures regarding CS required by national or international codes and standards such as Model Code Euro International Committee of Concrete (1993) now Federation Internationale du Beton (FIB), Eurocodes, ACI, RILEM, etc. are predominantly based on strength principles and limit state formulation. The durability aspect is a natural extension of the classical resistance verification where deterioration effects are normally neglected. The reliability is assessed through the given performance that must be delivered within the design service life, the so-called performance-based design. This approach can be adopted for a performance based on service life design. In the recent years design is related to durability through the analysis of carbonation, resistance to chloride ingress, improved freezing and thawing resistance, etc. The review of literature and some recommendations are presented referring to the design of structures aiming to attain greater durability of CS. The accent is put on the theory of reliability, failure probability and service life probability. The basics of this analysis are given through the principles of performances and service life, and deterministic and scholastic methods using the lifetime safety factor.*

Key words: *Concrete structures, service life, reliability, durability, failure, deterministic analysis, stochastic analysis*

1. INTRODUCTION AND TERMINOLOGY

The structure interacts with the environment (both micro and macroclimate). To describe the environmental actions it is necessary to describe them as surface temperature, humidity wetness and chloride conditions [2] and [8]. The response of concrete can be expressed as temperature and moisture conditions, carbonation depth and chloride penetration. The classification of environmental exposure is given in EN 1990 [3]. There is a complex set of multidisciplinary phenomena governing durability and long-term perform-

ance of concrete structures as a basis for service life design. The focus is on the structure and its interaction with the environment [4]. It is important to investigate and quantify the environmental actions and response of concrete structures depending on their quality.

However, civil engineering structures are complex systems whose components differ in reliability. For these structures **reliability** is the probability of a structure to fulfil the given function in its service lifetime, i.e. to keep the characteristics in given limits (performance) as defined in accordance with the defined regimen of use - consists of safety, durability and serviceability with the maintenance abilities [14]. Failure is described in terms of one or more limit states (connected to the impossibility of further usage of the structure or element) [18]. The structure is considered as durable in the actual environment as long as its function is acceptable. **Durability** is the capability of maintaining the serviceability of a structure over a specified time, or a characteristic of the structure to function for a certain time with required safety and corresponding characteristics, which provide serviceability. Structures contain elements that can last more than 100 years such as foundations, walls and floor slabs, while on the other hand there are components that need frequent replacing. The durability of a structure is its resistance against the actions from the environment surrounding the structure. However, some structures, depending on their quality and environmental aggressiveness, have not satisfactory durability [2].

Reliability can be assessed through providing performance during service life, i.e. through performance-based design. **Performance** of the structure is its combined short-term and long-term fulfilment of the functional requirements (safety, serviceability and appearance of structure during its service life). Functional requirements and corresponding properties could be: minimum load carrying capacity (concrete and steel strength, corrosion and spalls of concrete depth); maximum acceptable deformation (E-modulus, shrinkage, creep, thermal movement, and settlements); maximum penetrability for gaseous or liquid substances (concrete permeability, capillarity and diffusivity, and size and arrangement of cracks) [7].

The generally accepted aim of a design is "to achieve an acceptable probability that the structure being designed will perform satisfactory during its intended life" [6]. In order to construct a durable and reliable concrete structure (CS) it is necessary to design it for durability and provide required service life. **Serviceability** is viewed as the capacity of the structures to perform the functions for which they are designed and constructed within normal use conditions. **Service life** is the period of time after construction during which all properties exceed the minimum acceptable values when routinely maintained [11]. The terms lifetime and working life are also used in literature. The European standard for structural safety EN 1990 prescribes 50 years for buildings and 100 years for monumental building structures, bridges and other civil engineering structures. A service life design conditions the designer's choice of fundamental properties to fulfil all functional requirements during the target time. Defects in materials may lead to week serviceability of a structure.

The key step is defining a target service life. In practice there are three different types of service life depending on the type of considered performance: **Technical service life** (Fig.1) is the time of service until acceptable state is reached (failure). **Functional service life** is the expected time in service until the structure no longer fulfils the functional requirements. **Economic service life** is the time in service until the replacement of the structure is economically justified more than keeping it in service. The service life prob-

lem is mainly technical, with the following sub-aspects: mechanical and other structural performances; serviceability, and aesthetics. Real service life must not be shorter than nominal - normative life. The two phases of deterioration (Fig. 1) are [6]:

- The initial phase (period) in which there is no noticeable weakening of properties, except protective barrier (the duration of this phase is about 15 years). Corrosion occurs initiated by chlorides or carbonation;
- The propagation phase with active deterioration mechanisms that develop increasingly with time. The propagation period consists of the propagation with minor damage and the accelerated period (the duration of this phase is about 15 years). After that follow the accelerated period with widespread cracking and spalling of the protective layer (cover).

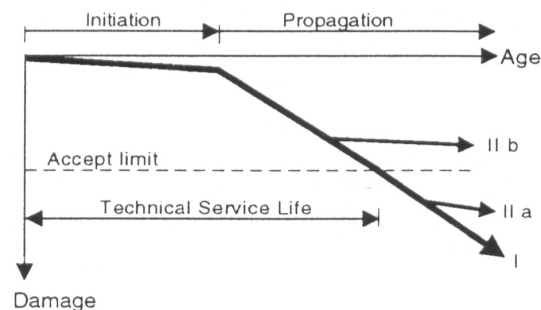


Fig. 1 Service life of concrete structures – a two-phase modelling deterioration

Apart from the materials of national and international associations [3], [5], and EN [11] and [12] that have been dealing with this field for the last 30 years, there is a large number of publications dedicated to the durability of concrete structure (CS). Besides, there were a few conferences on the topic. One of the best monographs dedicated to durability [2] presents the behaviour of concrete, deterioration mechanisms, structural investigations, repair and protection of CS. It describes a few case studies for buildings and engineering structures. A significant contribution to the introduction of a modern approach of designing CS for service life is given in [18], as well as in the publication Special issue on durability CS and in [9] and [10]. The paper [16] is contributed to the introduction of the concept of reliability and service life analysis. Additionally, papers [13], [14], [17] and [19] deal with the problem of modelling and computation of durability, which is the theme of the second part of this article that will be published in the next issue of the journal.

The codes provide only qualitative definitions of exposure and they fail to define the design life in relation to durability, i.e. achieving an acceptable level of reliability of the structure performance in its environment as a whole (regarding deflection, cracks and spalling, structural integrity and aesthetics). This is especially important when CS is exposed to an aggressive environment. It is very important to have basic understanding of the complex set of multidisciplinary phenomena governing durability and long term performance of concrete structures as basis for service life design.

Present design procedures are predominantly based on strength principles, and the design is increasingly being refined to address durability requirements (resistance to chloride ingress, improved freezing and thawing resistance, etc.). A certain level of durability, such as requirement for concrete cover to protect reinforcement under aggressive action from environment and industry is inherent with design calculation. Structures such as pavements and bridges have not achieved the desired service life; therefore, details providing long-term durability based on service-life should be taken into consideration when designing them.

The usual way of analyzing CS discusses the aspect of durability neglecting the effects of deterioration (weakening of mechanical properties). This is acceptable in structures of minor importance, but not for the important ones exposed to aggressive actions. For instance, pavements and some parts of bridges, garage parking, and underground structures in contact with contaminated soil do not achieve required durability. Therefore, it is necessary to design them by introducing the criterion of durability based on the analysis of service life (SL) [1]. In recent years in the world, durability of structures is introduced through the analysis of carbonation, chloride corrosion, and alternate freezing and thawing. The paper gives a wider review of literature and some recommendations of some international associations referring to the basics of the analysis and usage of the reliability theory [16]. The fundamentals of the theory, failure probability and service life probability are discussed. The basics of this analysis are given through the principles of performances and service life, and deterministic and scholastic methods using the lifetime safety factor.

2. SERVICE LIFE AND DURABILITY – REVIEW OF LITERATURE AND CODES

Reinforced concrete (RC) structures are designed in accordance with national or international codes and standards such as Model Code Euro International Committee of Concrete (1993), Eurocode 0 and 2, ACI 318, RILEM, etc. The minimum requirements to be fulfilled are stated in national codes and standards. Historical and traditional reasons influenced that codes and standards differ considerably from country to country. The modern design concept of CS durability has been developed mainly within CEB–FIP [4], based on consistent deterioration mechanisms engineering models. In Model Code basic requirement is: "Concrete structures shall be designed, constructed and operated in such a way that, under the expected environmental influences, they maintain their safety, serviceability and acceptable appearance during an explicit or implicit period of time without requiring unforeseen high costs for maintenance and repair" [3].

The Eurocode system has been chosen as the basis for design in the EU member states. Possible evolutions of a structure during its working life using a suitable "performance indicator" that is assumed to be a monotonously decreasing function of time. It can be expressed in terms of various units: mechanical, financial, reliability, etc. In all cases, after a certain period of time, the "performance indicator" decreases, for example due to corrosion of steel, carbonation of concrete, repeated opening of cracks in concrete member, spalling, etc. The principal requirement to be considered in the overall strategy for achieving durability: in particular, decision with regard to the life performance required from the structural members and whether individual members are to be replaceable, maintainable or should have a long-term design life.

The Eurocodes are based on the limit state approach in combination with a system of characteristic values and partial factors. In most cases durability concerns the serviceability of structures. In this paper some new formulations by adding deterioration processes in serviceability limit state are presented. In the cases where deterioration of the concrete structure might go on unobserved the durability problem can be directly associated with an ultimate limit state. The description of a limit state may require one or more limit state functions.

In EN 1990:2002 E [11] a structure shall be designed to have adequate: structural resistance, and durability. Durability including the choice of the design service life depends on environmental actions. The prevention of potential causes of failure requires reliability levels to be maintained. Design working life should be specified. Design working life (DWL) category 3 with indicative DWL for replaceable structural parts is 10 to 25 years; for building and other common structures indicative DWL is 50 years: monumental buildings, bridges, and other engineering structures.

The service life can be designed by using two principles: deem-to-satisfy rules, and performance-based design. The deem-to-satisfy rules are based on specifying a certain concrete composition and concrete cover, but the result is not a specified service life. The performance-based design is based on requirements of performance of the structure, and the result will be a long specified service life with limit states. The designer first defines loads the structure should resist. To verify if the loads exceed the resistance, the loads and strength must be compared. Action (load) must be resisted through selecting a combination of structural systems, element geometry, and material properties [8].

In **conceptual design** it is necessary to make a good decision in the early phase of the project. The basic formulae of durability design can be written according to these two optimal principles:

1. performance principle, and
2. service life principle.

The load can be mechanical and environmental. The structural design focuses on the structure's ability to resist the environmental impact imposed on the structure. Durability design comprises the design concerning the structure's ability to resist minimizing of the environmental impact imposed on the structure. Environmental design comprises the design of minimizing the environmental impact that the structure imposes on the environment during its entire life span, provided that structural and durability requirements are fulfilled [8].

Service life depends on structural design and detailing, mixture proportioning, concrete production and placement, construction methods and maintenance. The design of RCS aiming to ensure adequate durability is a complicated process [1]. If water or other fluid is involved in concrete degradation, concrete permeability is important. It is well-known that deterioration of concrete depends on the presence and transport of water or other fluid, i.e. concrete permeability (concrete pore structure, presence of cracks and microclimate at the concrete surface). Model Code presents the relationship between the concepts of concrete durability and performance [3]. Transportation of heat, moisture and chemicals, both within the concrete and exchange with the surrounding environment constitute the main element of durability. The element of design, material selection, execution and curing which determine the quality of concrete are illustrated in Fig. 1 [4].

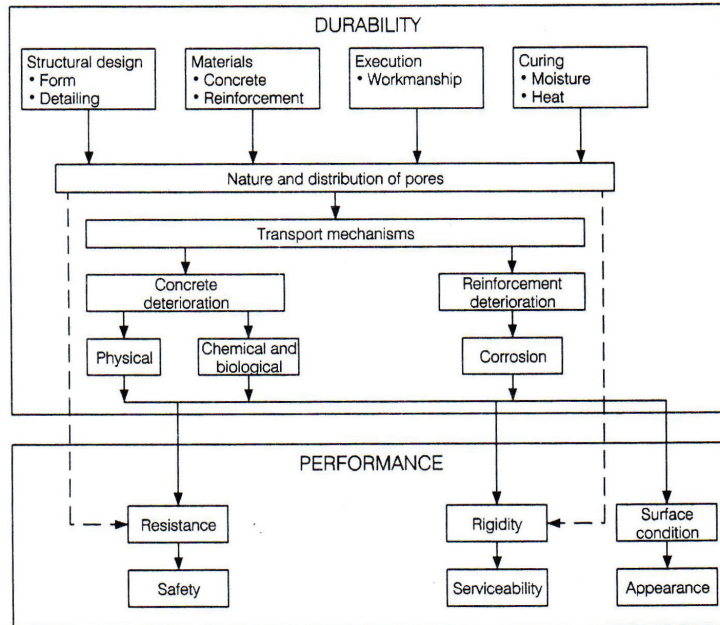


Fig. 2 Relationship between durability and performance, after [4]

The level of reliability determined in the initial phase of design should take into account the cause of failure (member with low ductility should be designed for a higher degree of reliability than the one for which a collapse occurs with limited consequences (risk to life, injury, potential economic losses and the social inconvenience). The rate of deterioration may be estimated and consequently the prediction of design service life, in the context of durability including: the use of knowledge and experience acquired from laboratory and field investigations; estimates based on the performance of similar materials in a similar environment, modelling degrading processes, and use of accelerated testing [9]. The long-term capacity depends on the degradation of concrete and steel. The minimum acceptable values for performance, or maximum acceptable values for degradation, are called durability limit states. Several mathematical models have been developed to predict service life of concrete subjected to degradation processes, as describe in Fig. 3.

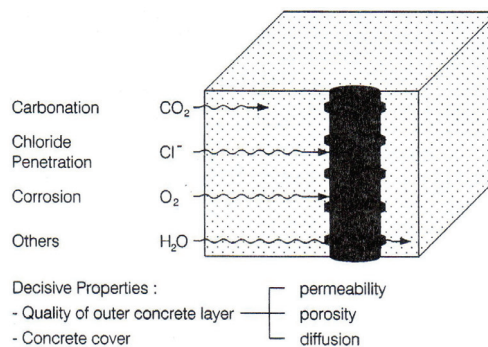


Fig. 3 Transport mechanisms for aggressive substances influence on concrete and reinforcement, and importance of the protective concrete layer – to protect the structure against deterioration, after [6]

With durability design we can verify that the intended service life can be achieved with an acceptable level of reliability. *Reliability* of the structure should be considered as its ability to fulfil the specific before mention requirements, including working (service) life. It is the probability of a system performing its required function adequately for a specified period of time under stated conditions. It is the probability that the structure should fulfil the given function in its service life, without exceeding the specified limit state. Reliability is expressed as a probability expected for a certain (specific) period of time, under specified conditions.

Performances are functions of time. When time is used in the evaluation of performance, various external factors, which provoke deterioration/degradation, must be considered. In this way performance is linked with durability. Degradation is gradual decrease in performance over time, i.e. opposite to performance. The concept of performance or degradation over time can be applied at different levels: buildings, structural component and materials and there may be interactions between levels. On the long run the load bearing capacity will depend on the degradation of concrete and reinforcement, and performance of structural elements must be evaluated by first analyzing the rate of change in performance on the material level. The minimum acceptable values for performance (or maximum acceptable value for degradation) are called durability limit state [5]

The theory of durability design is in principle based on the theory of safety (or structural reliability) used in structural design [5]. Reliability and failures must be addressed in probabilistic terms. In design service life the following procedures are used [1] and [11]:

- The selection of design actions and the consideration of material property deterioration,
- Comparison of different design solutions and choice of materials (balance between the initial cost and cost over an agreed period, i.e. life cycle cost,
- Management procedures for systematic maintenance and renovation of structures.

Designing of a new structure for a given service life or determining the remaining service life of the existing structure requires to [19]:

- Formulate the functional requirements to be fulfilled.
- Assess the aggressiveness of environment of the structure.
- Establish mathematical models describing the interaction of the material and environmental properties and deterioration mechanisms using the engineering judgment.

In the first step the designer must define actions/loads and assess the safety factor as multiplier. With durability design we must provide some structural measures and calculations to verify that the intended SL can be achieved with the acceptable level of reliability. The level of reliability is related to structural safety and serviceability and selected according to the consequences of failure and risk to life: low and consequences are small; medium and high. Extremely high degree of reliability (high risk) must be provided for nuclear power reactors and major dams; higher than normal (high risk) for significant bridges and public buildings with high consequences of failure; medium risk and normal degree of reliability for residential and office buildings; and low risk (lower than normal degree of reliability) for agricultural buildings [11].

Climatic actions and their intensities on structures such as wind, temperature, rain and snow vary in time [10]. The climate change is a great concern considering the origin of

the change in global temperature. In design, climate effects are taken into account by applying design codes, or on the bases of past observation of behaviour. Changes in climate will have an effect on the design loads. Structures are designed to have a minimum resistance to the actions (loads) on the structures or their parts.

The **deterministic design for durability** will still govern for some time, but with regular updating of the characteristics of the environment and improvements of the modelling of transport and deterioration mechanisms. Parameters that influence on durability are: the cement type and quality control of early age cracking, limitation of crack width, etc [12]. Their values depend on the environmental aggressiveness. **Probabilistic performance-based** service life design is used because of the variation of CS due to different structure properties of the structural part, concrete compositions and different location conditions. Modelling of environment and deterioration mechanisms is being developed on a probabilistic basis allowing reliability based service life design. Service life design methods are similar to the load and resistance – factor design procedure used for structural design.

Designers' guide EN 1990 [15] – the degree of reliability should be adopted so as to take into account: the cause and mode of failure (sudden collapse, low ductility-brittle element) should be designed for a higher degree of reliability; the possible consequences of failure in term of risk to life and economic consequences; the expense, level of effort and social and environmental conditions; the expense level of effort and procedure necessary to reduce the risk of failure. The levels of reliability related to structural resistance and serviceability can be achieved by the combination of the following:

- Preventive and protective measures;
- Measuring related to design calculations (representative value of actions and the choice of partial factor) and assessment of soil and environmental influences;
- Measures related to the design matters (basic requirements, durability including choice of the design SL) and choice of mechanical models and detailing;
- Efficient execution compliance with EN 1991 to EN 1999; adequate inspection and maintenance, and introduction of measures to prevent potential causes of failure and/or reduce their consequences, i.e. provided the required reliability.

The **durability design procedure** is the following [5]:

1. Specification of the target service life and design service life;
2. Analysis of environmental effects,
3. Identification of durability models for degradation mechanisms;
4. Selection of a durability factors and degradation mechanisms (depth of deterioration of concrete and corrosion of reinforcement, concrete cover, diameter of bars);
5. Calculation of durability parameters using available calculation models;
6. Possible updating of the calculations of the ordinary mechanical design (i.e. own weight of structures);
7. Transfer of the durability parameters into the final design.

The **deterioration of CS** is affected by the environment, and adequate measures need to be examined when considering the strategy to achieve durability. Concrete structures (CS) are exposed to different actions of environment and are vulnerable to damage as corrosion, and freezing and thawing. The use of materials that provide increased durability should be considered in the overall strategy for durability, for example epoxy-coated rein-

forcing steels or concrete with low permeability. The design should avoid structural systems that are inherently vulnerable and sensitive to predictable damage and deterioration. The shape of members together with their detailing will influence the durability of the structure. With increased durability, structural members should be protected from detrimental environments. Maintenance should be considered during the design. Provision should be made for inspection, maintenance and possible replacement [9] and [11].

In most cases durability concerns the serviceability of the structure. However, in cases where deterioration might go on unobserved the durability problem can be directly associated with an ultimate limit state. The description of a limit state may require one or more limit state functions. One of the consequences of the required reliability in the service life design of a structure is the fact that between the design service life and the mean service life a margin is present. This margin depends on the required level of reliability, the type of service life distribution and its mean value and scatter. In [11] are introduced three classes of consequences (CC3-high consequences for very great loss) CC2 for medium and CC1 for low consequences. Reliability classes may be defined by the β reliability index. Three reliability classes RC1, RC2 and RC3 may be associated with consequences class (CC1, CC2, and CC3). Minimum β values for 50 years reference period are (RC3=4.3; RC2=3.8 and RC1=3.3).

3. RELIABILITY AND METHOD OF DURABILITY DESIGN

The EN 1990 [11] is primarily based on deterministic (historical and empirical) method, semi-probabilistic (Level II) and full probabilistic (Level III) methods. In the Level II procedure, an alternative measure of reliability is conventionally defined by the reliability index β which is related to failure probability P_F , by:

$$P_F = \phi(-\beta), \quad (1)$$

where ϕ is cumulative distribution function of the standardised Normal distribution.

Relationship value β and P_F are shown in Table 1.

Table 1 Relationship between β and P_F

P_F	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}
β	1.28	2.32	3.09	3.72	4.27	4.75	5.20

The reliability of structure depends on both actions (loading) and properties (performance). For structural safety design is based on reliability analysis using probabilistic model for both the loads and resistance of the structure, and treated stochastically. The probability densities of the resistance R of a structure, and of the load effect S are predicted with adequate models.

The reliability P_R of the structure, in EN 1990 [11] marked with P_S , is the probability that the sample point falls in safe region, i.e., that the system would perform adequately for at least a specified period of time and under specified operating (service) conditions (reference period). Conversely, the probability of failure, P_F , designates the inability of a system to perform its intended function. It follows that

$$P_R + P_F = 1 \quad (2)$$

Let t denote time elapsed since the structure was put in service, i.e., the age of the structure. If the calculated P_F is larger than a pre-set target value P_0 , then the structure should be considered to be unsafe. For any set of structures that are in a failed state at age t , denoted with $F(t)$ which is called the *lifetime distribution function* for the set [14], and its complement (*the survival function*) is

$$G(t) = 1 - F(t) \quad (3)$$

The derivative of distribution function

$$f_L(t) = dF_L(t)/dt \quad (4)$$

is called the *failure rate function*. If the probability of failure for a period $(0, t)$ is plotted as a function of t , a monotonically rising function is obtained, increasing from 0 to 1 for t increasing from 0 to ∞ . This function is identical with the distribution function of the service life $F_L(t)$. The mortality, or hazard function, at time t is defined as the probability of failure per unit time conditional upon survival to time t ,

$$h(t) = f(t)/G(t) \quad (5)$$

When the set of structures is a population, these functions may be interpreted as probabilities. If t_d designated design life, then $P_F = F(t_d)$ is the *failure probability* and its complement,

$$P_R = 1 - P_F = G(t_d) \quad (6)$$

is reliability of the population. Structural reliability theory aims to predict or compare these probabilities from the attributes of a structures and its environment. Except in mass-produced structures or components, the reliability of a structure can rarely be determined by observation of the population [14].

The four measures of reliability are: conventional factor of safety (R/S), central factor of safety as a relation between expected value R/S , safety margin $M = (R - S)$ (in EN 1990 marked with g) and *reliability index* as a relation between safety margin and the number of standard deviations. It is reciprocal to the coefficient of variation of safety margin.

The theory of durability design based on the theory of safety is traditionally used in structural design. The strength R and actions (load) S are functions of a large number of stochastic variables and general are function of time [16]. The main criterion for reliability can be written as:

$$\text{FAILURE} = R < S; \text{ the probability of failure defined as: } P_f(t) = P\{R(t) < S(t)\} \quad (7)$$

If the probability density functions of all these variables are known, the probability density functions $f_R(r)$ for the strength and $f_S(s)$ for the actions can be derived (Fig.1). Probability of failure P_f is shaded area in Fig. 4 and 5.

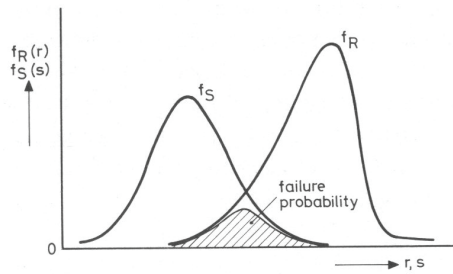


Fig. 4 Probability density function for strength (f_R) and action - load (f_S) and failure probability (shaded area) - have no physical or mathematical significance, after [16]

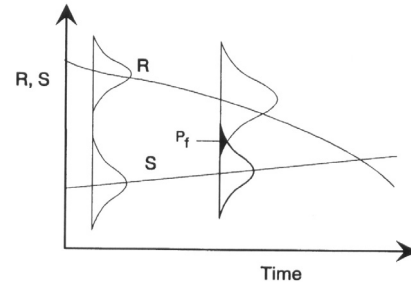


Fig. 5 Increase of failure probability

If R and S are both time-dependent, the minimum value of R will not necessarily coincide with the maximum value of S as described in Fig. 6 [14] and [16].

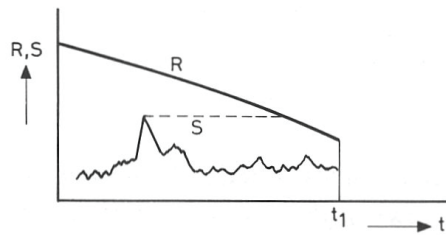


Fig. 6. The maximum of S is larger than the minimum of R , after the period considered, yet there is no failure, after [16]

Failure probability is the function of time and is bound up with the way in which R and S are defined. Point $t = 0$ of the period under consideration coincides with the point when the structure is put into service. The probability $P\{R(t) < S(t)\}$ is related only to a particular point of time and not to the period of time [18]. For the period $(0, t)$ it should be:

$$\begin{aligned} P\{\text{failure in } (0, t)\} &= 1 - P\{\text{no failure in } (0, t)\} \\ &= 1 - P\{R(t') > S(t') \text{ for } t' \text{ in } (0, t)\} \end{aligned} \quad (8)$$

For the whole period $(0, t)$ and governing actions S :

$$P\{\text{failure in } (0, t)\} = P\{R(t) < S(t)\} \quad (9)$$

Failure probability function has the character of a distribution function. If the service life is defined so that the event $(t_L < t)$ is identical with the event (failure in lifetime t) the distribution function of service life can be defined [5] as

$$F_L(t) = P\{t_L < t\} = P_f(t) \quad (10)$$

where F_L is the cumulative distribution of service life

The probability density function can be determined as the derivative of the distribution function:

$$f_L(t) = dF_L(t) / dt \quad (11)$$

At a certain moment the probability of failure can be determined as two probabilities: (1) the probability when $R < S$, at $S = s$, and (2) the probability when $S = s$, extended for the whole range of S . Considering continuous distributions, the failure probability P_f at a certain moment of time can be determined by using the convolution integral:

$$P_f(t) = \int_{-\infty}^{\infty} F_R(s) f_S(s) ds \quad (12)$$

where $F_R(s)$ = the distribution function of R ,
 $f_S(s)$ = the probability density function of S ,
 s = the common quantity or measure of R and S .

The straightforward solution of the convolution integral (12) is only available in a few cases, i.e. when the distributions of R and S are normal, but the integral can be solved by approximate numerical methods. The distribution of service life can be obtained by calculating the failure probability values at different moments of time.

Specification and design of the target service life are defined corresponding to the requirements given in common regulations, codes and standards (EN 1990, for instance). The design service life is determined by the equation:

$$t_d = \gamma_t t_g \quad (13)$$

where t_d = the design service life,
 γ_t = the lifetime safety factor, and
 t_g = the target service life.

The analysis of environmental effects includes identification of climatic conditions (temperature and moisture variations, rain, condensation of the moisture, freezing, solar radiation and aerial pollution, ground water, and contamination of soil by sulphates and chlorides, de-icing salt, abrasion due to traffic, etc.) [8] and [11].

In **stochastic durability design**, not only target service life but also the definition of maximum allowable probability of not reaching the target service life is necessary. It is called the probability of failure [18]. When failure is caused by degradation of materials the term "durability failure" is used. Theory of durability design is based on the theory of structural reliability. The basic formulae of durability design can be written according to two optional principles:

- performance (actions S , in EN 1990 effects of actions marked with E , are set into relationship with the performance), and
- service life principle (the service life t_L evaluated by a service life model must be greater than the required target service life t_g).

In deterministic durability design approach, actions (loads), resistance, and service life are used as deterministic quantities, and distribution of this function is not considered. The design formula is:

$$R(t_g) - S(t_g) > 0 \quad (14)$$

where t_g is the target service life.

In reality S and R are time dependent functions, while the service life principle design formula is:

$$t_L - t_g > 0 \quad (15)$$

where t_L is the service life function.

The design of structures is performed by selecting an appropriate combination of value design parameters in such a way that the condition (14) and (15) are fulfilled.

In stochastic design method the distributions of actions, response and service life are taken into account. The condition that the probability that the service life of a structure will be shorter if the target life is smaller than a certain allowable failure probability is written as:

$$P\{\text{failure}\}_{t_g} = P\{R - S < 0\}_{t_g} < P_{\text{fmax}} \quad (16)$$

or in the form:

$$P\{\text{failure}\}_{t_g} = P\{t_L < t_g\} < P_{\text{fmax}} \quad (17)$$

where left side of Eq. (16) is probability of failure of the structure within t_g , and P_{fmax} is the maximum allowable failure probability.

The problem can be solved if the distribution of service life is known.

Although the **lifetime safety factor** method is based on the theory of reliability, formulation of the design procedure returns to deterministic form. The design service life is determined by multiplying the target service lifetime safety factor:

$$t_d = \gamma_t t_g \text{ as Eq. (13)}$$

where: t_d – the design service life, γ_t – the lifetime safety factor, and t_g – target service life. With the performance principle or the service life principle can be written:

$$R(t_d) - S(t_d) \geq 0 \quad (18)$$

$$t_L - t_d > 0 \text{ as Eq. (15)}$$

The lifetime safety factor must be calibrated with results of stochastic design methods and the value depends on maximum allowable failure probability.

Distribution types that can be used for the evaluation of service life or performance of structures include the following distribution:

- normal - Gaussian,
- log-normal,
- exponential,
- Weibull and
- gamma distribution.

Experience has demonstrated that concrete structures are exposed to different actions of environment and are vulnerable to damage as corrosion and freezing and thawing. Damage considerably influences the service life of concrete structures. In performance design, the commonest assumption is that actions or resistance, or both, are normally distributed. By this approach R and S are normally distributed quantities; the failure probability can be determined by using the test index (in structural design β – reliability index) which is normally distributed:

$$\beta(t) = \frac{\mu[R,t] - \mu[S,t]}{(\sigma^2[R,t] - \sigma^2[S,t])^{1/2}} \quad (19)$$

When S or R is constant, index β has forms:

$$\beta(t) = \frac{r - \mu[S,t]}{\sigma[S,t]} \quad (20)$$

$$\beta(t) = \frac{\mu[R,t] - s}{\sigma[R,t]} \quad (21)$$

where r and s are constants.

As the means and standard deviations are dependent on time, so is index β . To obtain the distribution of SL the failure probabilities must be solved with several values of t . When R is constant and S time dependent the function is approximated by a degradation model/problem. Contrary when S is constant and R is time dependent function the problem is called a performance problem. When the performance principle is applied, the commonest assumption is that either the action or the resistance, or both, are normally distributed. When the service life principle is used, the distribution of service life is often assumed to be log-normal, i.e. normal on a logarithmic time scale [5] and [11]. Performance behaviour can always be translated into degradation behaviour, because degradation is a decrease in performance.

4. SERVICE LIFE PREDICTION AND LIFETIME SAFETY FACTOR

Lifetime model depends on the quality of condition model for material. The condition model, i.e. the condition of material is described with following function [19]:

$$\text{Condition} = \text{start condition} - \text{damage} \quad (22)$$

The simplified and the complex model of service life will be analysed in Part 2 of the paper, which will be published in the next number of the journal.

Four measures of reliability have been considered: conventional factor of safety (FS), the central factor of safety (CFS), the safety margin (S), and the reliability index β . The reliability index concept is a very popular indicator for probabilistically based design in structural engineering. Assessment of reliability is made entirely by comparing the calculated reliability index β with those found to be adequate on the basis of previous experience with the structure under consideration. The process begins with a mathematical model that relates the capacity (strength) and demand (actions) for a limit state of interest.

The lifetime safety factor depends on the maximum allowable failure probability, and the smaller the maximum allowable failure probability, the greater the lifetime safety factor. The lifetime safety also depends on the form of service life distribution.

With the aid of the lifetime safety factor the design problem returns to the form of deterministic design. The lifetime safety factor is the relation of mean service life to the target service life [5]:

$$\gamma_t = \frac{\mu(t_L)}{t_g} \tag{23}$$

where γ_t – the central lifetime safety factor,
 $\mu(t_L)$ – the mean service life,
 t_g – the target service life.

On this way the requirement of target service life, corresponding to a maximum allowable failure probability, is converted to the requirement of mean service life. This is convenience for the designer because designers operate with mean value. The mean service life evaluated by the service life model must be greater than or equal to the design service life:

$$\mu(t_L) \geq t_d \tag{24}$$

where $t_d = \gamma_t t_g - t_g$ – is the design service life.

The mean SL is not necessarily the same as the SL corresponding to 50% failure probability, which is the median SL.

The lifetime safety factor depends on the maximum allowable failure probability, and from of SL distribution. The meaning of lifetime safety factor for design according to the *performance principle* is illustrates in Fig. 7. This curves correspond to a situation common to the design problem of load-bearing capacity ($S=const$) and structural capacity $R(t)$ must be grater then S to avoided failure. The function $R(t) - S$ is called the margin of safety. The crossing point of the $R(t)$ curve with the minimum load effect S given the mean service life which equals the design service life. In the case of structural performance, S , is the load effect (in EN 1990, is called effect of action and marked with E), and in applications of durability design replace with minimum performance capacity, R_{min} .

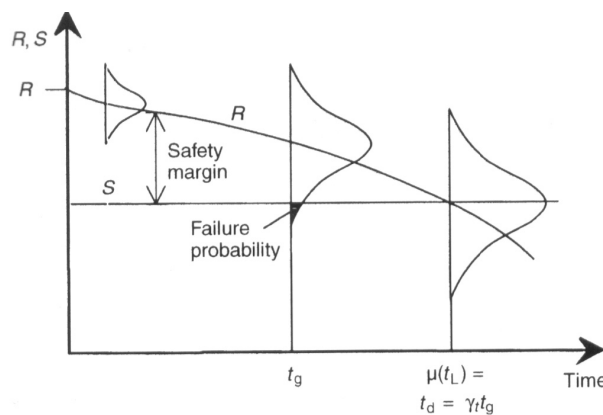


Fig. 7 The meaning of lifetime safety factor in a performance problem, after [5]

Performance behaviour can always be translated into degradation behaviour, because degradation is a decrease in performance. The transformation is performed by the following substitution:

$$R_0 - R(t) = D(t)$$

$$R_0 - S = R_0 - R_{\min} = D_{\max}$$

The principle of design in a degradation problem is shown in Fig. 8. $D(t)$ is the degradation effects of environmental loading on the performance of the structure. The curve $D(t)$ crosses the maximum degradation at the design service life, which must be longer than the service life (Fig. 8). The range $D_{\max} - D(T)$ is the safety margin. The diagram of the member forces extreme values represents the forces envelope for them the envelope of the possible influences for all the registrations. Known the correct values for lifetime safety factors is very important.

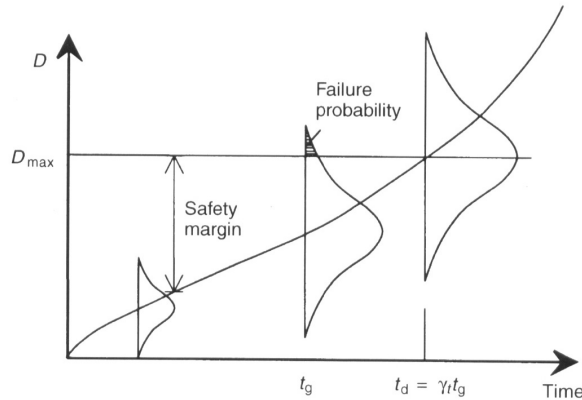


Fig. 8 The meaning of lifetime safety factor in degradation problem [5]

5. CONCLUDING REMARKS

The interaction between the concrete and the environment determines the possible deterioration mechanisms. The environmental design system of buildings and civil engineering structures, in which the selection of materials and structural shape, construction work, maintenance, and demolition and recycling should be established aiming to minimize resources and energy, to decrease hazardous substances, and control construction and demolition waste [8]. Design of durable structures contributes to the realization of a sustainable society. Besides design for durability (selection of materials and geometrical value) for prolonged service life, i.e. increased durability, it is very important to limit the following: CO₂ emission, water pollution, soil contamination, dust, chemical substances, etc.

The deterministic design for durability will still govern for some time, but only with regular updating of the characteristics of the environment and improvements of the modelling of transport and deterioration mechanisms. Parameters which influence durability

are: the cement type and quality control of early age cracking, limitation of crack width, etc [12]. Their values depend on the environmental aggressiveness. In [12] are introduced five degrees of aggressiveness of the environmental exposure according to Model-Code CEB-FIP (1993). In ISO based on the principles given in [8] the classification of environmental conditions and environmental management-life cycle assessment is presented. Service-life prediction models may be probabilistic, when service-life is expressed in the form of probabilistic distribution functions.

Probabilistic performance-based service life design is used because of the variation of concrete structures (CS) due to different structures properties of the structural part, concrete compositions and different location conditions. Modelling of environment and deterioration mechanisms is being developed on a probabilistic basis allowing reliability based service life design. Service life design methods are similar to the load and resistance-factor design procedure used for structural design.

When considering durability the pore structure of the material is an important issue. Deterioration is often caused by the transport of aggressive agents into concrete matrix, and the limitation of this process improves durability. Structures such as parking garage, pavements and decks of bridges do not achieve the desired service life, and need to be designed and detailed for long-term durability based on service-life consideration [17].

The quality of service life predictions depends on the capability of models used and quality of the input data. It is necessary to ensure viability of appropriate methods for the characterization of concrete to provide data for the testing and use of models [17]. Models for describing the deterioration mechanisms must integrate knowledge from a wide range of different disciplines, such as static, statistics, materials technology, design, construction and economy. Inefficient deterioration mechanisms are reinforcement corrosion and subsequently cracks and spallings of concrete. Main causes of corrosion (with presence of water) are chemical attacks, alkali-aggregate reactions, and freeze-thaw bursting. The development of these models and a more detailed methodology of durability analysis of CS is the topic of the second part of the paper. It presents and analyses the recommendations and technical regulations since they are essential under present conditions for the design of reliable and durable structures.

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PROJEKTOVANJE BETONSKIH KONSTRUKCIJA SA ASPEKTA TRAJNOSTI – DEO 1: OSNOVNE ANALIZE

Radomir Folić

Betonske konstrukcije (BK) se projektuju tako da zadovolje zahteve sigurnosti, upotrebljivosti, trajnosti i estetike u eksploatacionom veku. Aktuelni postupci proračuna BK, koji se zahtevaju nacionalnim i međunarodnim tehničkim propisima kao što su: Model propisa Evro-internacionalnog komiteta za beton (iz 1993.) sada Međunarodna federacija za beton (FIB), Evrokodovi, Američki institut za beton, RILEM (Udruženje za istraživanje materijala i konstrukcija) i dr., zasnivaju se na proverivosti i graničnih stanja. Aspekt trajnosti predstavlja prirodan nastavak provere klasične otpornosti pri čemu se efekti deterioracije zanemaruju. Pouzdanost se procenjuje preko obezbeđenja performansi BK tokom eksploatacionog veka (SL), tzv. projektovanje zasnovano na performansama. Ovaj pristup se može usvojiti za neku performansu zasnovanu na projektovanju eksploatacionog veka. Poslednjih godina proračun trajnosti vezuje se za analizu karbonizacije, otpornosti na dejstvo hlorida, na naizmenično zamrzavanje i otapanje i dr. U ovom radu dat je pregled literature i nekih preporuka sa ciljem postizanja veće trajnosti BK. Naglasak je na Teoriji pouzdanosti i verovatnoći otkaza i analizi eksploatacionog veka. Prikazane su osnove ove analize koristeći princip performansi i eksploatacionog veka, i metode: deterministička, stohastička i korišćenjem faktora sigurnosti.

Ključne reči: Betonske konstrukcije, eksploatacioni vek, pouzdanost, trajnost, otkaz, analiza, deterministička, stohastička.