The loss of durability in reinforced concrete structures

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Abstract. Durability becomes a very important factor in design. Concrete, and in particular reinforced concrete constructions, are sensitive to environmental impacts (actions on construction) and also have a strong environmental impact (e.g. pollution, noise, dynamic interactions etc.). The feature of concrete, which is durability, has an impact on the reliability of the structure. The time during which the structure has a fixed durability should be one of the parameters in the design of the structure. Durability despite the passage of time of use can be restored.

1. Introduction

During the design of buildings, there is often no expected regeneration or renovation of parts or of the whole building. Reduced resistance due to many years of buildings exploitation is included in partial safety coefficient because of fact that phenomenon of durability is a stochastic process. But due to over-exploitation and unfavourable terms such as increased chemical activity on building, structures lose their reliability before the termination of operation of the facility.

2. Basic principles of reliability

At present, concrete as building material is widely used in the world and plays a dominant role in the broadly understood construction industry. Due to the expected longer serviceability of concrete structures, the requirements for aesthetics, acoustics, small (or at least not growing) harmful effects of these constructions on the environment are also emerging. Increasingly, the requirement has been raised to design a disposal (demolition) of an object after the use of a structure exploits completely.

The engineering structure of a building object should generally meet the inequality describing the reliable use of the object [1, 2, 3].

The basic equation of reliability of RC construction wall can by described in following equation (1) [3]:

$$R \geq \mathrm{A} \tag{1}$$

where: R – construction resistance, i.e. strength, uncracking state etc., A – actions on construction, i.e. loadings and displacements affecting on construction.

This equation is used by engineers in stresses quantities, or resultant forces. Forces are compressive or tensile or bending moments.

When designing a construction, two limit states are being considered: Ultimate Limit State (ULS) and Serviceability Limit State (SLS) where equation (1) should be satisfied. Resistance is understood as:

- ability to transfer stresses in structures induced by interactions,
- ability to reduce excessive deformations, deflections and cracks.

In addition, other structural properties such as frost resistance, abrasion, vibration damping, tightness, fire resistance, chemical resistance, etc. are being considered. The interaction is understood as:

- fixed, variable and unique loads, static and dynamic,
- displacement of supports,
- thermal and fire loads,
- moisture effect, etc.

The requirements for objects in these two limit states are complemented by the requirements for durability as an equivalent element in design. Reduction of durability of construction material can cause beginning of object destruction acceleration process.

Generally in ULS R is regarded as a strength A as stresses. In SLS R is allowable deflections or allowable cracks and A is static deflection or calculated crack. R is not simply limits stresses and A is not simply loads of snow, winter, pressure etc. Equation (1) has not simple, i.e., the linear form. It involves many parameters appropriate for the loads and strength. Equation (1) can be written in the following formula (2):

$$R - A \geq 0 \quad (2)$$

or knowing that right side of equation (2) is function we can define function of safety or reliability as (3):

$$f(R - A) \geq 0 \quad (3)$$

Function f(R – A) is depended of many variables, generally X variables which are random values. We can write it as sequence variables X_i (4):

$$X = X_i \quad (4)$$

X_i variables are associated one with another with formula of reliability (1). They form a set Ω of variables in the inequality (1). The reliability measure is the probability of survival (P_B) calculated as (5):

$$P_B = \int_{\Omega} f_x(X)dx \quad (5)$$

Where: $f_x(X)$, is the probability density function of the variables X_i, $X=(X_i)=(\Delta T_{,ph}, T_{,w}, a_{ct}.., h, t, a, f_{cd}, f_{yd}, a_{th}...)$, Ω is the safe set (Fig. 1).

There are the following X_i:

- parameters connected with acting loads “A”
- parameters connected with chimney wall strength “R”

Generally calculation of probability P_B employs probability of failure as a measure and require a knowledge of the joint distribution of all random value parameters. It is Level-3.

Probability of non-failure can be written in terms of safety margin Δ (6):

$$f(R - A) = \Delta = R - A \geq 0 \quad (6)$$

is $P_B=P(\Delta>0)$. As an alternative to P_B, a reliability index is often defined as $\beta_B=\Phi^{-1}(P_B)= -\Phi^{-1}(P_F)$, where $P_F=1-P_B=\int_F f_X(X)dx$ is failure probability and F is the failure set. β is interpreted as minimum distance between central point and limit state surface (Fig. 1). In general this integral cannot be computed analytically. Method of solving this integral is rather difficult because of its complexity. There are many methods based on simplification and additional assumptions ([1, 4]). Sometimes we can simplify the problem to the basic variables which are jointly normally distributed and the failure surface is a hyperplane. Then the failure probability is simply $P_F = \Phi(-\beta_C)$ where β_C is second order moment reliability index for safety problem. We can use another reliability indexes in the place of β_C as for example general β_G or ([1]) reliability index β_{HL}. In another words we can use methods of Level-2 or even Level-1 to evaluate the index of reliability.

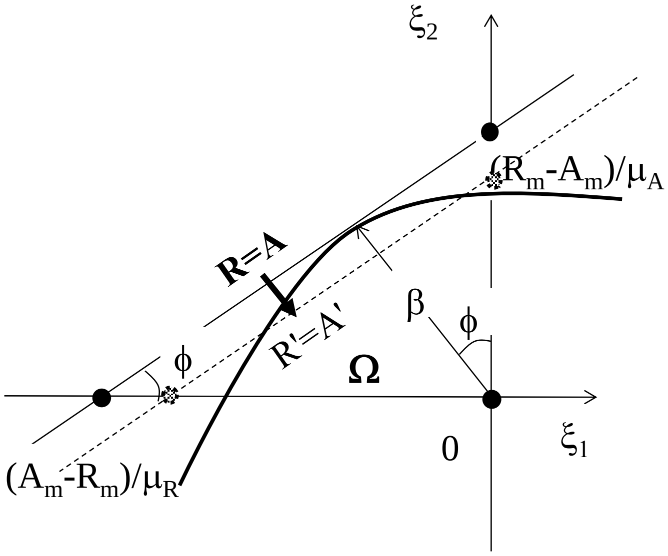

Figure 1. Index β as a minimum of distance between tangent to limit state surface and central point; area Ω is safety state of construction computing methods

The limit condition Δ=0 implicate reliability index (7):

$$\beta \leq \Delta_m/\mu_d \tag{7}$$

and (8):

$$\Delta_m = (R_m - A_m)/(\mu_R^2 + \mu_A^2)^{\frac{1}{2}} \tag{8}$$

where R and A with index m denotes mean value of R and A, μ denotes standard deviation.

If standardized variables $\xi_i=(x_i-x_{im})/\mu_I$ are used, then β is the shortest distance to limit surface (9) (Fig.1).

$$\beta = (R_m - A_m)/\sqrt{(\mu_R^2 + \mu_A^2)} \tag{9}$$

When R and A are separated than index β in Level-2 is divided to two indexes for resistance and action consecutively (10).

$$(A - A_m)/\mu_A \geq \beta_A;\ (R - R_m)/\mu_R \geq \beta_R \tag{10}$$

Simplifying safety phenomenon Δ=R-A to one dimension space margin of safety area Δ is shown on Fig. 2 where:

$$\Delta A = A^d - A^k;\ \Delta R = R^d - R^k \tag{11}$$

Where [5]:

A^k is characteristic value of A (i.e. equal to 95% of the statistical distribution quantile),

R^k is characteristic value of R (i.e. equal to 5% of the statistical distribution quantile),

A^d is design value of A,

R^d is design value of R,

A^d, R^d - design value is increased or reduced value compared to the characteristic value using the partial safety factor of loads or material - ϕ_A or ϕ_R.

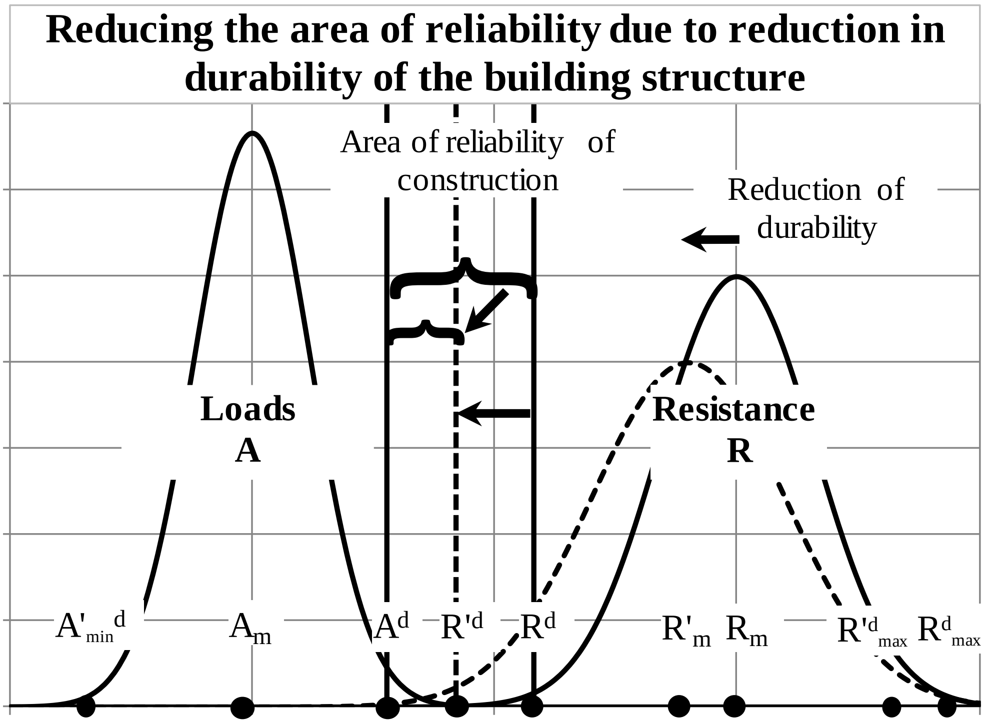

Figure 2. Reducing the area of reliability due to reduction in durability of the building structure

Lowering in time values of strength parameters caused increase of coefficient of variation and decreasing of design value of strength. So consequence is decrease of durability of constructions elements. Increasing value of μ_A and μ_R cause the line R=A to move to line R'=A' into the Ω area, which area is reduced.

After many years of exploitation some concrete constrictions need to be reconstructed, strengthened or changed in their static solution. It is almost certain that each construction built more than thirty or even twenty years ago must be strengthened. Strengthening of concrete constructions e.g. chimney, silo walls, slabs, foundations etc., hereinafter referred to as RC constructions, can be carried out generally in two ways, according to formula (1) [3]. Decreasing of value of left side of this equation and increasing value of right side of this equation separately or simultaneously makes concrete construction more safety.

Decreasing value of A can be achieved by decreasing mean value of loads or decreasing the value of coefficient of variation of loads separately or simultaneously.

RC structures (Fig. 3, 4a) built 40 years ago in many places in Poland were renovated and most of them were strengthened. During the test of strength parameters of the walls it was found that values of coefficients of variation of parameters as steel bar diameter, distance between bars, concrete cover, concrete strength are rather high. They achieve value 0,2 - 0,4. That means the value of strength of RC constructions is significantly reduced. As a result of carbonation, of many cracks, loss of concrete cover strength of whole construction is decreased.

3. Definition of durability

According to [2] the term "material durability" is understood as the ability guaranteed by the manufacturer to maintain the mechanical, functional and aesthetic properties of the material during the projected lifespan of the object.

Figure 3a. Concrete cover and corroded steel bars of silo wall

Figure 3b. Chimney wall destruction

Durability at the design level of the structure means that the structure is used within the expected time without the need for additional security or repairs.
Eurocode recommendations [4] do not provide information for planned periodic repairs to restore the material's original properties.
The durability of the material, is not a specified feature, is a random variable and a function of time that can be described by the cumulative function, e.g. (12):

$$F(t) = P(t < T \backslash R, \zeta) \tag{12}$$

where T is the time studied (during which repairs are not foreseen), R is the examined characteristic, e.g. strength, ζ coefficient characterizing the variability of the examined characteristic, e.g. the amplitude of the maximum to minimum stress ratio.

The durability of the materials that comprise the construction depends on many factors. The first factors fall into the broadly defined impact of the environment on the object. These include: the type of impact on the object, the duration of its exploitation, the method of construction, the quality of performed inspections of the most important construction elements during construction.

Some examples of constructions which lost resistance before the time of the end of design life are industrials reinforced concrete chimneys or silos (Fig. 3, 4) [4,5].

Renovation of the durability of the walls of chimneys and silos required many steps. Most of concrete cover and corroded steel bars were replaced (Fig. 3). Corroded reinforcement was replaced and new bars were added, additional reinforcing mats were in use or prestressed tendons, cracks were fulfilled by injection. In opinion of Authors of these repairs primary durability was recovered (Fig. 4b).

Figure 4a. Chimney before repair

Figure 4b. Chimney after repair

4. Increasing the durability of concrete using composite materials

The traditional methods of strengthening reinforced concrete structures are already very well recognized and widely used. In some cases, especially when the strengthening of the structure must be done in a short period of time without causing significant difficulties in the functioning of the building, the use of modern composite reinforcements may be a good solution. Depending on the functional requirements of the structure and other restrictions, the appropriate reinforcing material should be selected.

The most popular group of strengthening composite materials are Fibre Reinforced Polymers (FRP) that consist of high strength fibres embedded in epoxy resin matrix. These composites are available in the form of fibres, which are impregnated with resin at the site of strengthening the construction, as well as prefabricated tapes or fittings that are attached directly to the structure. This type of strengthening allows to gain high increases of load-bearing capacity but to increase its efficiency mechanical anchoring [7] or even prestressing [8] can be used. The main problem of this type of strengthening is melting of epoxy resin after exceeding glass transition temperature (T_g) of around +50°C [9]. When this unfavourable phenomenon occurs, composite loses its stiffness and strengthening effect. Therefore, the use of FRP composite strengthening is not effective when structure works in high temperatures or fire resistance is needed.

When better elevated temperatures resistance is required there is an alternative for FRP composites – Fabric Reinforced Cementitious Matrix (FRCM). Unlike FRP composites, FRCM system uses mineral matrix that is not as sensitive to high temperatures and fire as epoxy resin that has been shown in research [9]. The typical way of FRCM composite application is shown in fig. 5.

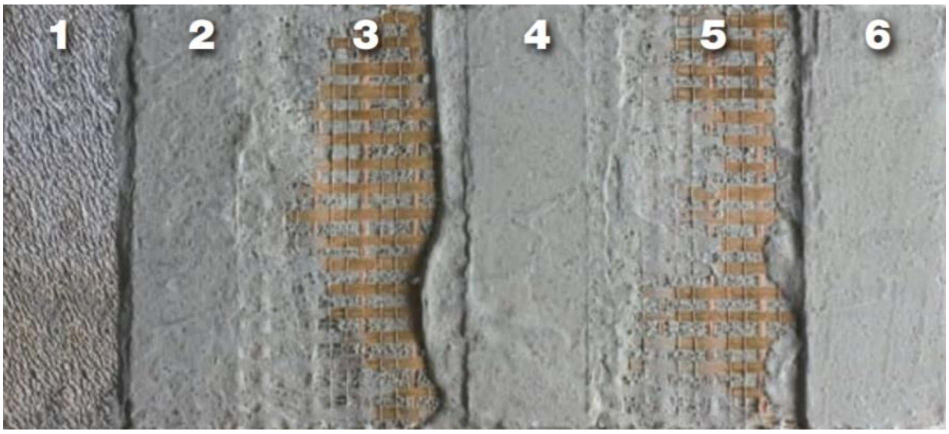

Figure 5. Typical way of FRCM composite application [10]

The main problems of FRCM composites are low strength of mineral mortar that results in debonding of the composite or fibres slippage and low penetrability of the matrix inside the fibre bundles that causes telescopic effect [11]. The loss of FRCM composite effectiveness can be partially enhanced by proper anchorage of fibres, which is under study [12]. FRCM composite system can be also successfully used in beam shear strengthening [13,14]. An additional advantage of FRCM over FRP is its lower sensitivity to concrete surface preparation (smoothness and humidity) that is helpful in practical use of strengthening composites.

In the case of large damages of the reinforced concrete structure, it is noteworthy that in the first place before strengthening with composite materials it is necessary to restore damaged elements, fill up the defects and stop the negative corrosive processes occurring in concrete and steel. The role of composite strengthening is to increase the lacking load-bearing capacity of the structure and the reversal and stopping of negative processes in concrete must be done using different methods.

5. Conclusions

The durability of the structure after years of operation can be increased by restoring the designed quality of the structure. In the case of a cracked structure, this usually means replacement of the cover, removal of corrosion of reinforcement bars, use of injections, restoration of wall monolithicity, repair or application of additional thermal, anti-moisture and chemical insulation. In some cases new generation composite materials such as FRP or FRCM composites might be helpful to allow high strength gains without adding much dead loads to the structure.

Constant control of the behavior of the concrete structure by measuring the deformation of structural elements, load control helps maintain good technical condition of the structure.

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