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SERVICE LIFE OF THE ENGINEERING STRUCTURES SUBJECTED TO ENVIRONMENTAL IMPACTS

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TRWAŁOŚĆ KONSTRUKCJI BUDOWLANYCH PODDANYCH ODDZIAŁYWANIOM ŚRODOWISKOWYM

STRESZCZENIE: Niniejszy artykuł przybliża aktualny stan wiedzy na temat metod projektowania konstrukcji budowlanych na okres użytkowania, którego głównym celem jest zapewnienie odporności konstrukcji na przekazywane na nią wpływy środowiskowe. Omówiono metody oceny trwałości konstrukcji i ich weryfikacji zgodne z wytycznymi norm ISO oraz wiedzy technicznej zawartej w literaturze naukowej. Ideą tych metod jest analiza środowiska eksploatacji konstrukcji, mechanizmów transferu, czyli przenoszenia się oddziaływań środowiskowych na elementy budowlane, procesów wewnętrznych i zewnętrznych powodujących ich degradację oraz ilościowych efektów degradacji. Realizuje się to zgodnie z zapisami obowiązujących norm budowlanych, które wykorzystują metody deterministyczne i probabilistyczne. W szczególności analizie poddane zostały istniejące metody probabilistyczne, wśród których można wyróżnić pełne podejście probabilistyczne, podejście półpropabilistyczne z częściowymi współczynnikami bezpieczeństwa oraz metodę stanów granicznych. Zamierzeniem opracowania jest zwrócenie uwagi na istotność doprecyzowania zaleceń projektowania konstrukcji inżynierskich na okres użytkowania.

SŁOWA KLUCZOWE: okres użytkowania, konstrukcje inżynierskie, trwałość, projektowanie, oddziaływanie środowiska

Introduction

Each building structure is exposed to damaging factors such as environmental conditions, natural ageing, deterioration of performance, and damage resulting from construction or operation during the service life cycle. The processes of destruction can lead to a reduction in the utility of components and materials to such an extent that the internal structure of the building will no longer fulfil the relevant design criteria such as the load capabilities and the planned design life will get shorter. To avoid premature destruction of the construction, we can find many useful practical rules and guidance concerning the extension of the life of the structure in the construction standards, for example, the use of a special protective coating of the steel elements of a building that are exposed to an aggressive environmental agent or excessive temperature.

Furthermore, as a result of international research grants, some design procedures have been worked out, making it possible to predict adverse factors affecting the deterioration of the building with regard to constructions made of concrete and reinforced concrete (for example the programme Britt/ UERAM[1]).

Limit states design

In line with the basic requirements of design standards, the structure should be designed to absorb all aversive influences of the environment expected during the processes of construction, installation, and usage of the building according to the intended purpose during all of the planned design working life. The construction should fulfil all the requirements with the proper level of reliability without excessive costs.

Properly designed construction should be characterized by the required resistance and durability. In the case of fire emergency, the load capacity of the structure should hold the building for the time necessary for the evacuation. The construction should also be resistant to unpredicted events such as explosions, impacts, or the consequences of human error.

Environmental factors that may affect the durability of the structure should be taken into account in the selection of structural materials, the type of system design, and the technical requirements of the building. To accurately assess the durability of the structure, it is recommended that the method of quantitative assessment of the effects caused by environmental agents be used.

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1 Britt / UERAM Program. DuraCrete 1996–1999. DuraNet 1998–2001. Darts 1997–2004.

These basic requirements for resistance, serviceability, and durability of structures should be met by the selection of appropriate materials and proper system design and also by determining and carrying out the appropriate control procedures at the stage of creation of design, material production, and installation of the elements, and during the use building.

The required durability and reliability of the building must be ensured by designing the structure following the guidelines of the Eurocodes on construction, taking measures to ensure quality. The structure should be designed in such a way that except for the impacts on the building caused by the environmental factors and with the expected level of maintenance of the structure, the building's performance will not decrease below the desired level. Environmental conditions affecting the durability of the structure should already be determined at the design stage so that appropriate preventive measures can be taken in time.

In the current design practice, buildings are designed using deterministic and probabilistic methods. Deterministic methods are based on comparative methods and empirical research methodology. The probabilistic methods can be divided into the full probabilistic approach, the semi-probabilistic approach with partial safety factors, and the method of limit states.

The basic demands of durability can be expressed by Equation (1), in which the lifespan of a structure or its component t_S shall not be less than the period of the project design t_D:

$$t_S \geq t_D \tag{1}$$

In the case in which the structure is protected for a limited time against adverse environmental influence (e.g. galvanized steel parts, protective coatings on wood, ...), the life of the structure can be represented by the formula:

$$t_S = t_{start} + t_{exposed} \tag{2}$$

where:

t_{start} – the time needed to initiate degradation of the element,

$t_{exposed}$ – use time after the initiation of degradation.

During the use time t_S, the construction meets the design requirements, and in the project period t_D, which is specified during the stage of planning, the proper functioning of the building or its component is ensured. The numerical value of the project period is usually given in the design Eurocodes (Table 1).

Tabela 1. Orientacyjne okresy projektowe obiektów budowlanych

Object category	The design life (years)	Examples of objects
1	10	Temporary structures
2	10-25	Interchangeable parts for construction of ordinary constructions
3	15-30	Agricultural constructions
4	50	Construction of buildings and other ordinary structures
5	100	Construction of monumental buildings, bridges, and other engineering structures

Source: BS EN 1990: 2002 Eurocode – Basics of structural design.

The construction usability period t_S is the result of many factors, such as the time of use of elements and components of design, applied management and control procedures, and current repairs. Parts and components whose planned service life is shorter than the planned design life of the entire structure must be replaced. Renovation or repair of the building components should be included in the design life period.

In the full probabilistic format, the probability of structural damage P is estimated, and then it is checked whether the calculated probability is less than or equal to the target probability P_{target} established in the design stage, according to the following formula:

$$P(t_S < t_D) \leq P_{target} \quad (3)$$

$$\frac{t_{sk}}{\gamma_s} \geq t_D \quad (4)$$

Examining the stability of the structure using this method is based on a comparison of the forecast of the utility period t_{SP} and value of the design life t_D according to the formula:

$$t_S = t_{SP} \geq t_D \quad (5)$$

The method of the limit states currently includes three limit states design. The ultimate limit state (ULS) refers to the construction safety. In the serviceability limit state (SLS), an excessive deformation of the structure disabling its proper functioning is subjected to the assessment. The border span limit state (ILS) corresponds to the beginning of the process of construction degradation[2]. The basic requirement for the ultimate limit state can be expressed by the formula:

$$R(t) \geq Q(t) \quad (6)$$

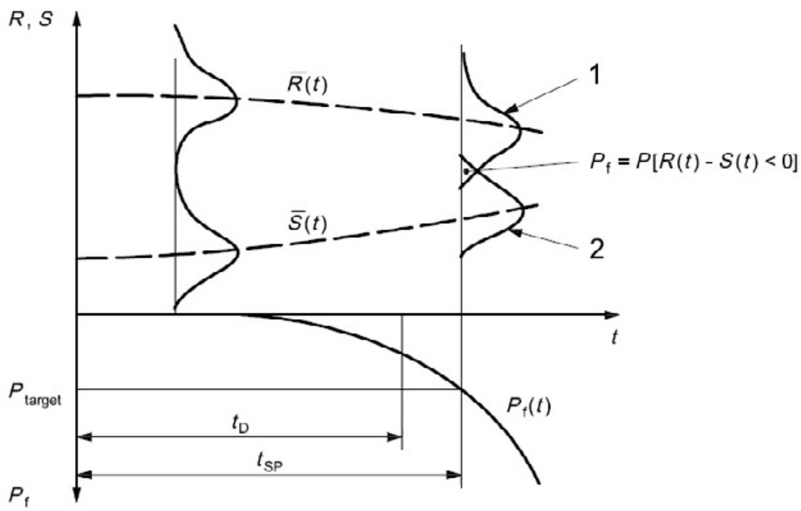
where:
$R(t)$ – working load limit.
$Q(t)$ – the impact on the structure.

In the state of the serviceability limit, the deformation or displacement of structures should not exceed the acceptable values:

$$S(t) \leq S_{lim} \quad (7)$$

The condition for the durability limit state can be presented by Formula (8) and shown in graphical form (Figure 1):

$$P(t) = Pf\,[R(t) - S(t) \leq 0] < P_{target} \quad (8)$$



KEY: 1 probability density function of *R(t)*
2 probability density function of *S(t)*

Figure 1. Mathematical model for predicting service life of the structure t_{sp}
Source: ISO 13823: 2008: General principles of the design of structures for durability.

2 CIB W80 / RILEM 71-PSL 1987, *Prediction of the service life of building materials and components*, "Materials and Structures" 1987 No. 20, p. 115.

Designing the building structures, focusing on durability

The general requirements for structural engineering for durability using the method of limit states are described in ISO 13823[3]. In this method, the durability of the structure is defined by analysing the environment where the structure is used, the mechanisms of transfer of the natural factors on the elements of the structure such as external and internal processes causing degradation, and the quantitative effects of this processes. A schematic diagram of this method is presented in Figure 2.

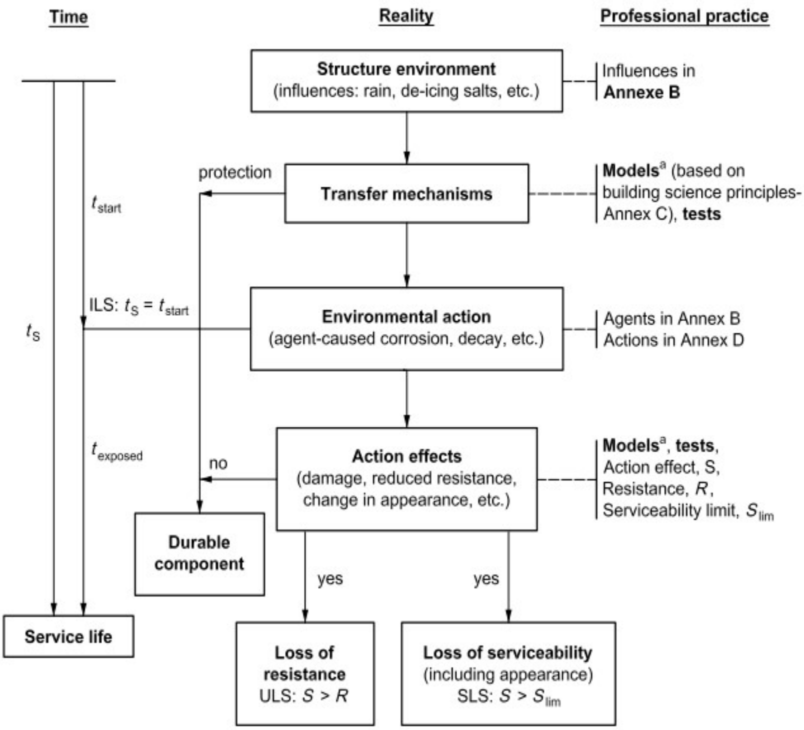


Figure 2. Design durability limit state

Source: ISO 13823: 2008: General principles of the design of structures for durability.

In a first step, it is necessary to specify the operating environment of the structure. This includes all the elements of the environment surrounding the structure, which gives rise to environmental impacts that degrade construction elements such as moisture, temperature, solar radiation, and

[3] ISO 13823:2008: General principles on the design of structures for durability.

others. Examples of types of operating environments of the structures and the corresponding impact on the structures are shown in Table 2, and descriptions of the parameters of the environmental impact are presented in Table 3.

Mechanisms for transferring the environmental impacts onto the structural elements are called transfer mechanisms. These are physical phenomena such as gravity, condensation and drainage, and capillarity actions that accelerate or prevent the degradation processes of structural components.

Table 2. Types of structural environments and exposure conditions

Environment	Environmental agents
Outside – atmosphere	Rain, snow, or ice Air constituents (nitrogen, oxygen, argon) Air pollutants (Chlorofluorocarbons – CFCs) Temperature and humidity Solar radiation
Outside – ground or water	Water Soil constituents Soil spills/leaks Road salt
Inside	Humidity and temperature Contaminating materials Water and sewage Stored chemicals Activities causing wear

Source: CIB W80 / RILEM 71-PSL 1987. "*Prediction of the service life of the building its materials and components*", Materials and Structures, 20 (1987) 115.

Table 3. Description of parameters of agents causing environmental action

Influences	Environmental agents	Examples of parameters
Moisture (constituents)	Solid (ice, snow) Liquid (rain, condensation) Gas (water vapour)	The period of humidity (TOW) Relative humidity (RH)
Moisture (contaminants)	Chlorides, acids, sulfates	Exposure time (TOE) Relative humidity (RH) pH Concentration
Air (constituents)	Oxygen, carbon dioxide	Exposure time (TOE) Concentration

Influences	Environmental agents	Examples of parameters
Air (contaminants)	Oxides, particulates, aerosols	Exposure time (TOE) Concentration
Ground (constituents)	Sulfates and other salts	Exposure time (TOE) Relative humidity (RH) pH Concentration
Air (contaminants)	Chemicals from spills and leaks Chlorides from road salt Induced electrical currents	Exposure time (TOE) Relative humidity (RH) Time (T) pH Concentration
Biological life	Microorganisms, insects, animals, plants	The period of humidity (TOW) Relative humidity (RH) Time (T) Geographical location
Temperature	Freeze–thaw cycles, heating	Number of cycles (F–T)
Solar radiation	UV radiation, IR radiation	Exposure time (TOE) Relative humidity (RH) Time (T)
Use or exposure	Wear, abrasion	Exposure time (TOE) Load

Source: The authors' own study based on CIB W80/RILEM 71-PSL 1987. "Prediction of the service life of building materials and components," *Materials and Structures,* 20 (1987), 115; E. Vesikari, "The effect of coatings on the service life of concrete facades," *Proc. 9th International Conference on Durability of Building Materials and Components* (Australia: Brisbane, 17–21 March 2002).

Modelling of the deterioration process requires an understanding of the transfer mechanisms and environmental actions on the structural components. This should include knowledge of the parameters of the materials and the components and microclimate in the vicinity of the used components. Examples of transfer mechanisms are shown in Table 4.

As a result of the transfer mechanisms of environmental actions in the materials, internal and external processes take place. They may be positive (e.g., by strengthening the natural ageing of the steel material) or negative (e.g. embrittlement of the plastic material under the influence of UV radiation). Degradation processes taking place within the material, such as steel corrosion, biological decay of timber, or concrete shrinkage, are the chemical, electrochemical, biological, and physical actions causing degradation or deformation of the structural components. They are dependent on the properties of building materials and the type of environment surrounding the structure.

Table 4. Transfer mechanisms causing environmental actions

Transfer mechanism	Examples
Direct exposure	UV on exterior surface materials Rain on the roof or wall surfaces Ground moisture
Gravity	Water traps in lap joints Ponding on „flat" surfaces Rain penetration into roofs Staining of building face by water runoff
Air/vapour pressure	Rain penetration into walls Condensation in building envelopes due to air leakage and vapour diffusion
Capillarity or surface tension	Penetration of rain and groundwater through porous materials due to capillarity tension Migration of salts within porous materials
Kinetic energy	Driving rain on wall surfaces and penetration through openings
Permeation	CO2 and water ingress into concrete causing corrosion Vapour transmission through building envelope materials
Convection	Air leakage through gaps in building envelopes
Condensation	Vapour condensation inside thermal bridges
Diffusion	Chloride ingress into hard concrete

Source: The authors' own study based on E. Vesikari, op. cit.

The results of degradation of the structure are the measurable effects of environmental agents (Table 5). They are characterized by one of the limit states – ultimate serviceability or durability – being exceeded. The effects can result in the destruction of structural elements, reduction of the load capacity, additional stresses, or loss of use performance due to excessive deformation.

The most critical factor in the degradation of building structures is acid rain, which is a type of precipitation at pH less than 5.6. It includes fatty acids produced from the reaction of water wit gasses emitted into the atmosphere (sulfur dioxide, sulfur trioxide, nitrogen oxides, carbon dioxide). Industrial pollutants emitted to the atmosphere from fuel combustion or the industry increase the acidity of the environment by decreasing the pH to below 5.0.

The danger level of building walls due to moisture penetration is characterized by the driving rain index for vertical surfaces (DRI) according to DIN ISO 15927–3[4] expressed in metres and the average wind speed in metres per second. The values of the indicator express the safe, average, and heavy levels.

[4] PN-ISO 15927–3:2010 Hygrothermal performance of buildings. Calculation and presentation of climatic data – Part 3: Calculation of a driving rain index for vertical surfaces from hourly wind and rain data.

Table 5. The effects of degradation depending on the type of structure

Material	Service environment	Transfer mechanism	Degradation processes	Action effects
Steel	Outside	Humidity condensation	Atmospheric corrosion	Reduction in the thickness of the components
Reinforced concrete	Inside and outside	Diffusion of chloride ions	Carbonation of concrete	Reduction of the cross-section of the reinforcement, reducing the durability of the concrete
Wood	Water	Direct exposure	Fungal decay	Biological decomposition of the material

The time of wetness (TOW) of material is another of the basic parameters of the description of environmental hazards. Corrosion processes occur in the environment where the surfaces of metal structures are covered with a thin layer of water. This happens at above-zero temperatures at a relative humidity of 80 to 90%. The period of exposure to moisture of the external components of the structure depends on the shape, for example, whether the water can flow away from the structure[5].

Exposure of plastics [polyvinyl chloride, polycarbonate, polymethyl methacrylate, polyethene, or polypropylene] that are used for the production of roofs and walls to sunlight has a detrimental effect on their viability. Ultraviolet radiation breaks the chemical bonds of the polymers, causing various types of damage: stiffening, cracking, or discolouration. The exposure time (TOE) of these elements to sunlight is important when assessing the degree of degradation of structural elements[6].

The frost resistance – resistance to cyclic processes of freezing and thawing (FT) – is an important feature of wall materials in the autumn–winter season. This property is crucial in maintaining the sustainability of the building materials and construction. Water that penetrates the centre of a construction subjected to repeated freezing and thawing can affect the properties of the building material, for example, reducing its mechanical durability.

To reduce the impact of adverse environmental actions on structures, it is advisable to take appropriate preventive measures at the stage of design and construction. The most important steps are developing a general concept of

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5 J. Bródka, M. Broniewicz, *Design of Steel Structures According to the Eurocodes,* Rzeszów 2014.

6 E. Vesikari, *The effect of coatings on the service life of concrete facades*, Proc. 9th International Conference on Durability of Building Materials and Components, Australia: Brisbane, 17–21 March 2002.

a building with enhanced resistance to environmental influences, the selection of appropriate materials, and the development of construction details and proper construction work, ensuring an adequate quality control system and periodic inspections. It is also crucial to use protective measures, such as shaping the connections and the use of protective coatings. Examples of such measures are presented in Table 6.

Table 6. Examples of design and detailing to minimize environmental actions

Transfer mechanism	Examples
Barrier	Coatings: zinc on steel, protective paint coating on wood Impregnation of wooden components Sealants of joints and contact surfaces Damp-proofing and waterproofing of foundations Waterproof membranes of garages and bridge decks Air/vapour barrier system in building envelopes
Drainage	Detailing to avoid water traps Detailing to avoid rain penetration in building walls Drips to deflect moisture away from lower components Applying dewatering systems
Ventilation	Detailing to promote exchange of moist air with dry air in rooms

Conclusions

The problem of durability of a structure can be described by two basic variables: R, the structural integrity against environmental factors causing degradation throughout the design life, and S, the environmental impacts on the structure during its service life. At the stage of construction design and selection of materials, it is necessary to check whether the durability of the construction is higher than the design performance requirements and utility demands that may occur during the service life. Both the resistance of the structure R and the environmental impacts S are time-dependent values. When designing the structure with regard to the aspects of load capability and stability, the time factor is often ignored, and with regard to determining the durability of the construction, time is a very critical element that reduces the structure's resistance.

In general practice, building structures are designed based on a set of rules and recommendations presented in the normative standards of design. The subject of design life of the structure is not yet regulated in appropriate normative acts. As a result of international research grants, some design methods have been elaborated. Moreover, the publication of ISO 13823 was the first step towards the codification of the problem of determining the durability of building structures exposed to environmental impacts. The ISO norm does not provide strict methods of design life of the structure or introduce any partial safety factors that could reduce the resistance of the structure to external influence due to harmful environmental agents. However, it is an essential element in the overall design assumptions of the project aimed at determining the durability of the design and unifies the conceptual scope associated with this field of design.

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The contributions of the authors in the creation of this article

Prof. Mirosław Broniewicz, PhD Eng. – contributed 40%: the concept of the article and essential input

Filip Broniewicz, Eng. – contributed 30%: a literature review and technical and organizational contributions

Karolina Dec, Eng. – contributed 30%: a literature review and technical and organizational contributions

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