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SAFETY OF THE REINFORCED CONCRETE STRUCTURE IN SELECTED DESIGN AND EXECUTION PARAMETERS

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Abstract: The chapter discusses selected standard parameters for the safety of a building structure, which include reliability, serviceability and durability. The current Eurocodes in Poland formulate the concept of reliability for the period from the design concept to the end of the intended service life. Hence, the reliability of the structure is influenced by factors related to the stage of investment preparation, design works, execution as well as the use and maintenance of the facility. The Eurocodes formulate otherwise obvious requirements as to the qualifications of engineering and labor staff, supervision and quality control of the implementation of design and construction works, the requirement to use materials compliant with the applicable standards, and proper maintenance of the facility and use in accordance with the assumptions. Such requirements were not formulated in previously binding standards. According to the author, the appearance of such provisions should be treated as a direct assumption of high standards.

The issue of the value of service loads and the accuracy of their mapping was discussed. Attention was also paid to the problem of significant complexity of the climatic load patterns. The Ultimate and Serviceability Limit States are explained. In terms of impacts, the issue of their value and possible calculation schemes was raised. In terms of materials - concrete and steel, the general research and relationships between the most important strength properties are discussed.

The issue of geometric dimensional deviations and the method of their adoption were also discussed, with particular emphasis on the reinforcement cover at the design and execution stage.

Keywords: Safety, factors, normatives, building, RC structures.

1. INTRODUCTION

The basis for the design of building structures in Poland today is the PN-EN 1990 standard, commonly known as Eurocode 0. This standard lists several assumptions that must be met in order for the design to meet the reliability requirements. It consists of load capacity, serviceability and durability. It should be mentioned that it takes an even broader approach to the issue of the pre-standard *fib*-MC 2010 (*fib* Model Code 2010, 2014) for concrete structures: it also covers maintenance (including technical condition assessment, maintenance and strengthening) and the period of demolition of the facility. It was quoted here because one of the purposes of its development is to set the direction for the development of new standards in the field of reinforced concrete structures. The tool of the investor, designer and facility manager that covers the entire life of the facility is BIM, i.e. Building Information Modeling.

In Eurokod 0 (PN-EN 1990, 2010), it is assumed that people with appropriate qualifications and experience will work on the project. The same requirement shall be specified in respect of execution operators. The design and construction process must be carried out under supervision and with adequate quality control of the work.

Construction materials and products are also required to comply with that standard and the following Eurocodes, as well as performance standards, or with technical specifications. Eurocode 0 also requires that the facility be maintained in proper technical condition and that it is used for its intended purpose.

It seems that the easiest to meet is the criterion of qualification and experience of engineering staff, but mistakes made by this staff at the design or construction stage (Czarnecki L., 2008), (Kulas T., 2008) are not uncommon. A serious problem of workmanship is also the shortage, and often even the lack of highly qualified workers (Kus J., 2020), which, combined with the lack of proper technical supervision, leads to serious errors resulting in a further reduction in the durability and safety of the facility.

The aim of this work, resulting from the issues presented above, is to articulate selected parameters shaping the safety of the object in the design and implementation phase.

2. METHODOLOGY FOR ENSURING THE SAFETY OF A CONSTRUCTION OBJECT

The reliability requirement formulated in Eurocode 0 specifies that the structure is properly designed, if it is able to absorb all the effects and influences that may occur on it during construction (PN-EN 1991-1-6, 2007) and use (PN-EN 1991-1-1, 2004), and that it is suitable for its intended use during its intended life. The impacts (colloquially loads) that may occur on the structure are primarily the impacts resulting from its intended use and climatic impacts, which include wind (PN-EN 1991-1-4, 2008, snow (PN-EN 1991-1-1-3, 2005) and seasonal temperature changes (PN-EN 1991-1-5, 2005). In addition, the impacts of random events, such as explosion and impact, as well as human errors should be taken into account, depending on the specificity of the structure. The requirement is that the structure "has not been damaged disproportionately to the cause". So, for example, in the event of an explosion in a multi-family residential building, the area of damage should be limited by the use of "bleed-off barriers", which, undergoing destruction, will transfer the pressure caused by the explosion outside the building (PN-EN 1991-1-7, 2008).

Eurocode 0 does not impose a requirement to limit the fire damage zone (it results from fire regulations), but it imposes compliance with the requirement of maintaining the load capacity of the structure within a specified time. The concept of fire resistance class is used here.

The specified requirements should be met at the design stage by selecting the right materials, adopting the appropriate static diagram, properly calculating the structure and designing all necessary construction details. The standard also recommends conducting proper supervision of design works and production of elements, execution works and supervision of use (e.g. the problem of snow retention on the roof), as well as carrying out periodic inspections of the facility.

2.1. Ultimate States

Designing on the basis of Eurocodes (PN-EN 1990, 2010) is carried out according to the limit states: Ultimate Limit State (ULS) and Serviceability Limit State (SLS). The main design method is the partial factor method. Briefly, it can be said that the limit state method consists in checking whether the design values of the effects of the actions do not exceed the permissible value for a given state.

Ultimate Limit States are used to check the possibility of loss of static equilibrium, internal damage or excessive deformation of a structure or its part, and the possibility of destruction or excessive deformation of the substrate, as well as the possibility of fatigue failure. In the case of checking the possibility of loss of static equilibrium, the design value of the destabilizing and stabilizing effects is compared. In the other two cases, the effect of actions expressed in terms of the induced internal forces and load capacity is compared. The values of the coefficients and impacts are determined using statistical methods based on many years of observations of their variability.

When calculating the structure for the Serviceability Limit States (PN-EN 1992-1-1, 2008), it is most often checked whether the structure meets the requirements of not exceeding the permissible deflection of the crack width and the size of vibrations, for the sake of comfort of use, durability and functions of the structure. Two calculation methods are allowed: the exact one, the result of which is the numerical value of the analyzed feature compared with the limit values, and the abbreviated one, which gives the answer whether the SLS may not be met. If the answer is yes, the exact method should be applied. The probability of obtaining an incorrect result results from the simplifications and comparisons used in it as well as references to steel tests with a yield point outside the assumptions of the Eurocode.

2.2. Actions

The Eurocode (PN-EN 1990, 2010) uses the term "design value" of the actions (E), which in practice means that when calculating according to ULS, the actions take values (greater or less than those given in the standard, depending on which load is more unfavorable). However, in the calculations according to SLS, values equal to the standard values are assumed.

The effect of external influences for ULS can be expressed by the formula (1) taking into account the partial factors:

$$E_d = \gamma_{Sd} \cdot E\{\gamma_{fi} \cdot \psi_i \cdot F_{ki}; a_d\} \tag{1}$$

where: γ_{Sd} - partial coefficient taking into account the uncertainty of the model of impact effects or modeling of actions (for permanent actions the value of the coefficient was assumed 1.35 with the possibility of reduction to 1.15, and for variable loads 1.5); it is the design value factor (ULS) of the action that significantly increases the values of the internal forces; γ_{fi} - partial coefficient of the impact determined taking into account the possible deviation of the *i*-th action value from the representative value (it can take values both greater and less than 1.0, thanks to which the most unfavorable values can be assumed according to the considered design situation); ψ_i - coefficient equal to 1.0 or expressing the so-called values: combinational, frequent or quasi-constant of the variable impact (i.e. the real part of the load that may occur alone or with other variable loads - takes values less than 1.0); F_{ki} - characteristic value of the impact, best determined on the basis of statistical data, assuming a certain probability of not exceeding the unfavorable side during the adopted reference period (load variability observation period), *d* - calculation value of the geometric quantity, i.e. the dimension of the cross-section).

The performance actions specified in the standards are generally assigned value ranges with an indication of the preferred value (PN-EN 1991-1-1, 2004). Their distribution on the surface of the partition is taken depending on the purpose of the calculations. For example, when calculating internal forces in a specific floor, loads on others can be considered as so-called "localized", that is, assume only one distribution pattern. However, on the calculated floor, all real load patterns should be considered, but if the floor is loaded with actions of different values on different parts, Eurocode 1 (PN-EN 1991-1-1, 2004) allows replacing these actions with one, the most unfavorable one. The method of applying this recommendation depends on the designer, who should not only analyze the impact values, but also take into account the sizes of individual loaded fragments and the impact of the adopted solution, first of all, on safety, but also on the economic aspect of the investment. When calculating multi-storey structures, Eurocode 1 introduces a reduction factor for the loads on the adjacent storeys in relation to the calculated one, assuming a low probability of a situation in which the superimposed actions occur on the adjoining storeys with the maximum value. Obviously, such an approach does not threaten the security of the facility, as it is based on long-term observations and statistical analyzes.

The way of loading the structure with climatic influences such as wind, snow and temperature is much more complicated. Relevant Eurocodes (PN-EN 1991-1-1-3, 2005), (PN-EN 1991-1-4, 2008), (PN-EN 1991-1-5, 2005) provide quite detailed rules for accepting and distributing the values of these actions, however, the degree of complexity of the problem with large bodies of objects and the lack of mathematical formulas for many cases of curved structures is significant and in practice may lead to underestimation of internal forces, therefore, in such and similar cases, it is of great importance for the accuracy of the calculations has the level of experience of the designer. This has an impact on the safety of the structure, as it can cause local cracking in the areas of underestimation and reduce durability or comfort of use.

The effects E_d calculated as the sum of the effects of component actions cannot be greater than the design resistance Rd, which is determined from the expression (2):

$$R_d = \frac{1}{\gamma_{Rd}} \cdot R\left\{\eta_i \cdot \frac{X_{ki}}{\gamma_{mi}}; a_d\right\} \tag{2}$$

where: γ_{Rd} - partial factor due to the uncertainty of the load capacity model and geometric deviations, if not taken into account otherwise, η_i - conversion factor taking into account, inter alia, the scale effect, the influence of humidity and temperature on the characteristic value of the property or product X_{ki}, γ_{mi} - partial factor for the product or properties.

2.2. Materials

The physical and mechanical properties of the materials are determined on the basis of the standards related to the Eurocodes. These are properties such as, for example, volumetric weight, porosity, water absorption, strength, yield point, modulus of elasticity, formability, etc. Such tests must be carried out in certified laboratories. Building materials and products must have approvals and certificates of approval specifying the values of features and intended use. An example of marking a reinforcing steel bundle is shown in Fig. 1.

Fig. 1. Designation of a reinforcing steel bundle

In the case of determining the strength properties of concrete, which are directly relevant for the design calculations according to ULS and SLS, it is allowed to test only a few samples (Neville, A.M., 2012), which, due to many years of experience and detailed development of testing and calculation procedures, is sufficiently safe. The basic parameters tested are: compressive strength and modulus of elasticity, tested in the direct test. The tensile strength is most often tested in a splitting test and converted. The 5% or 95% quantiles of the statistical distribution of the examined features (depending on the feature) necessary for the calculation of the structure are calculated using the appropriate formulas given in Eurocode 2 on the basis of the average value of the feature. The aforementioned Eurocode binds the average compressive strength and the characteristic strength (5% quantile) with the formula (3):

$$f_{cm} = f_{ck} + 8 \tag{3}$$

where: f_{cm} - average cylindrical compressive strength of concrete, f_{ck} - characteristic cylindrical compressive strength of concrete, which is a 5% quantile of strength distribution. The number 8 represents the value of the standard deviation multiplied by the parameter of the statistical distribution. The standard deviation was assumed to be constant for all grades of normal and high-strength concrete included in Eurocode 2, regardless of the age of the concrete. It is still debatable whether the standard deviation or the coefficient of variation should be a constant parameter (Torrenti, J.M., Dehn, F., 2019). The first parameter was adopted in the *fib* Model Code 2010 prenorm (Muller et al, 2013).

Reinforcing steel that can be used for design according to Eurocode 2 is mainly characterized by the values of the mechanical properties. The two basic requirements are ribbing on the surface of the rod and the yield point with values ranging from 400 MPa to 600 MPa. The steel is divided into 3 classes: A, B and C depending on the deformability and the ratio of the tensile strength to the yield point. Both these features are tested according to the PN-EN ISO 15630-1: 2019, PN-EN ISO 15630-2: 2019 standards. They should be carried out on a minimum of 10 samples, and if the steel cannot be qualified to the appropriate class, the test should be extended.

Experience has shown that the 5% quantile adopted now and in earlier standards for determining the basic mechanical properties of concrete and steel gives, with a sufficiently high level of diligence in construction works, an appropriate level of construction safety.

An important parameter for the durability of the structure is the minimum amount of reinforcement - the so-called degree of reinforcement required due to cracking and influencing the stiffness of the structure and deformability. The issue of the influence of the amount of reinforcement on deformability has been and is still being investigated (Blikharskyy et al, 2021). In fact, only in the case of lightly loaded elements it decides on the amount of the distributed reinforcement. In other cases, the load-bearing condition is decisive.

2.3. Geometric features The dimensions of the structure elements used to determine the value of the effects, i.e. the own weight, are assumed in the form of nominal values of a_{nom}. If, on the other hand, the deviation of the cross-section dimension or other geometric feature may affect the reliability of the structure, it should be taken into account in the calculations in accordance with the formula (4) (PN-EN 1990, 2010):

$$a_d = a_{nom} \pm \Delta a \tag{4}$$

where: a_d - computational value of the feature, a_{nom} - nominal value, Δa - deviation.

The reinforcement cover, the role of which is to protect the bars against corrosion, is determined in accordance with the formula (5):

$$c_{nom} = c_{min} + \Delta c_{dev} \tag{5}$$

where: c_{min} - minimum deviation determined according to the aggressiveness of the environment, the diameter of the rod and the arrangement; Δc_{dev} - deviation assumed for safety reasons (Eurocode 2 gives three types of deviations, but two of them are recommended to be equal to 0). It is recommended to assume the deviation of the cover in the range from 5 mm to 10 mm for monolithic structures and from 0 mm to 10 mm for prefabricated structures. The value depends on the level of control of the works (Czerińska k., Pacana A., 2019) and the accuracy of the equipment used. In the case of prefabricated structures, the deviation can be reduced even to 0mm if defective elements are rejected. In practice, the deviation is most often assumed to be 10 mm. The reason is the lack of the recommended deviation value in the national (Polish) annex to the standard.

Eurocode 2 also gives rules for reducing or increasing the nominal cover. It depends on the planned service life, the concrete class used, the possible impact of concrete works on the arrangement of the reinforcement and the degree of advancement of the concrete quality control. The cover is also increased when architectural concrete is used or when concrete is laid directly on the ground.

The design specifies the nominal cover. However, it is allowed to both increase and decrease the cover due to inaccurate construction. However, the permissible error limits do not reduce the durability compared to that required in the design. Table 1 shows the permissible values of the performance deviations:

Table 1
Permissible deviations of the reinforcement cover in accordance with PN-EN 13670: 2011

Section dimensions *b* i *h*	**Tolerance class**	
	I	**II**
≤150 mm	+10 mm, $-\Delta c_{dev}$	+5 mm, $-\Delta c_{dev}$
400 mm	+15 mm, $-\Delta c_{dev}$	+10 mm, $-\Delta c_{dev}$
≥2500 mm	+25 mm, $-\Delta c_{dev}$	+20 mm, $-\Delta c_{dev}$
In the case of foundations, the deviation in tolerance class I can be increased to 40 mm.		

Source: (PN-EN13670, 2011).

The 1st tolerance class achieves the fulfillment of design assumptions and all functional requirements for a given facility.

Fig. 2 illustrates the importance of proper reinforcement cover for the durability of a reinforced concrete structure:

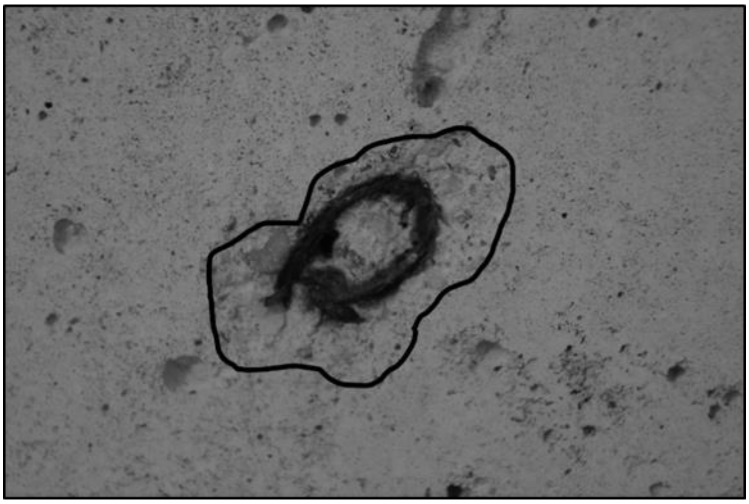

Fig. 2. Concrete spatter due to corrosion of the tie wire

Fig. 2 shows the effect of the environmental impact 2-3 years after the completion of the works. The curve line shows the loss of concrete around the tie wire loop. Which has been twisted on the outside of the reinforcement frame instead of inward. The regulations require the use of sufficiently thick cover both for structural elements of the reinforcement and for any other steel element. In the presented case, the length of the defect is about 6 cm and the depth is about 1 cm. The presented case of improper looping of the binding wire is a common defect that proves insufficient supervision of construction works and low qualifications of the workers. First of all, meeting the standard requirements for cover is very important for the durability of the structure (Tworzewski, P., 2017), because the proper protection of the reinforcement against corrosion prevents serious damage to the structure and failures caused by the bursting of concrete by peeling steel.

3. CONCLUSION

The development of experimental research and the resulting changes to standards increase the achievable level of structural reliability in many ways. On the other hand, there is a noticeable decline in the quality of construction works resulting from the lack of sufficiently qualified workers. A large part of structural defects is also caused by the lack of proper qualifications of designers and insufficient design supervision.

Providing the designer with the highest possible level of reliability and safety of the facility requires knowledge of design and construction regulations, the use of materials appropriate in terms of quality, selection of static solutions and design procedures. On the other hand, a very important aspect is the economic aspect articulated in the Eurocodes, which recommends balancing the costs that would have to be incurred to meet the SLS conditions with the costs that would be incurred in repairing the damage. Designing large-scale and multi-storey buildings requires particularly in-depth control due to the complexity of works and the financial and social consequences of an emergency.

BIM is a type of facility information management that, through the way it collects and the type of information it collects, increases the security of the facility in every phase of its "life cycle". It is also a platform for the exchange of information between the investor, designer, contractor and user.

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