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ANALYSIS OF THE MOST COMMON DAMAGES IN REINFORCED CONCRETE STRUCTURES: A REVIEW

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Reinforced concrete structures are often subjected to various negative environmental influences, reducing their reliability and durability. Main engineering tasks include extension of their life cycle, assessment of durability, reliability and residual service life. This requires reliable assessment of existing damages due to negative environmental impacts. Deterioration of RC structures is complex issue, which should be considered with the account of various factors. Damages and defects should be assessed, according to different criteria: degradation degree, type, time and cause of formation, etc. Article provides detailed analysis of the most common damages in RC structures on the basis of thorough literature review of this issue. Also, the classification of reasons for decrease of bearing capacity is proposed. Additionally, are discussed corrosion mechanisms and specifics of stress-strain state in corroded RC structures.

Key words: RC structures; damages; durability; residual load-bearing capacity; corrosion.

Introduction

Nowadays, reinforced concrete, as one of the most common building materials, is widely used both in mass housing construction and for unique buildings and structures. However, despite high efficiency of reinforced concrete structures, they are often subjected to various negative environmental influences, which reduce their reliability and durability. This material should be considered as complex multi-component heterogeneous system with synergistic properties, which on the one hand allows its effective use in wide range of structures, and on the other hand causes the ambiguity of its stress-strain state in the presence of various negative impacts. The possibility of efficient use of the RC structures` residual load-bearing capacity in design situations, which are close to the limit state, is often determined by the degree of their actual wear. Thus, it is necessary to assess the deviation of their actual strength parameters from the design values. In this case, the important issue is also to analyze the actual stress-strain state of reinforced concrete structures on the basis of field surveys (Blikharskyy Y., Kopiika, 2019).

Execution of main engineering tasks involves the optimal use of existing construction funds, extension of their life cycle, assessment of their durability, reliability and residual service life. This requires reliable assessment of existing damages and the level of degradation of structures, which is the result of negative environmental impacts (Blikharskyy, Kopiika, 2021).

The aims and objectives of the study

The main purpose of this article is thorough analysis of the most common damages in reinforced concrete structures. The research provides detailed review on existing studies of this issue. In addition, the classification of reasons for decrease of RC structures` load-bearing capacity is proposed. Corrosion, as one of the most common reasons of RC structures` deterioration is discussed more broadly. Main stages, mechanisms and specifics of stress-strain state are highlighted and analyzed.

Review of scientific sources and publications

It can be noted, that the problem of modeling the work of reinforced concrete structures in the case of aggressive external influences, as well as the assessment of progressive damages and changes in the stress-strain state of the structure has become significantly relevant in recent scientific research (Chandru, 2021; Lobodanov et al, 2018). Therefore, detailed literature review on the damages and defects in RC structures is necessary, as well as reliable scheme of their classification according to various parameters and aspects.

The most common concepts for classification of damages in RC structures

Thorough analysis of the possible reasons of reliability decrease in reinforced concrete structures requires detailed classification of damages and defects. This issue was emphasized in the number of previously published works (Bossio et al, 2016; Lobodanov et al, 2018; Blikharskyy et al 2019). For instance, in article (Blikharskyy et al, 2019) is proposed to divide all the causes of damages to reinforced concrete structures into the following groups: environmental, technological and extraordinary influences.

On the DCC-104 International conference (Javor, 1991) was also proposed to use the following criteria for classification of damages and defects in RC structures: the degree of damage, the part of the building in which the defects are detected, the time of formation, the cause and provenance of the defect (see Fig. 1).

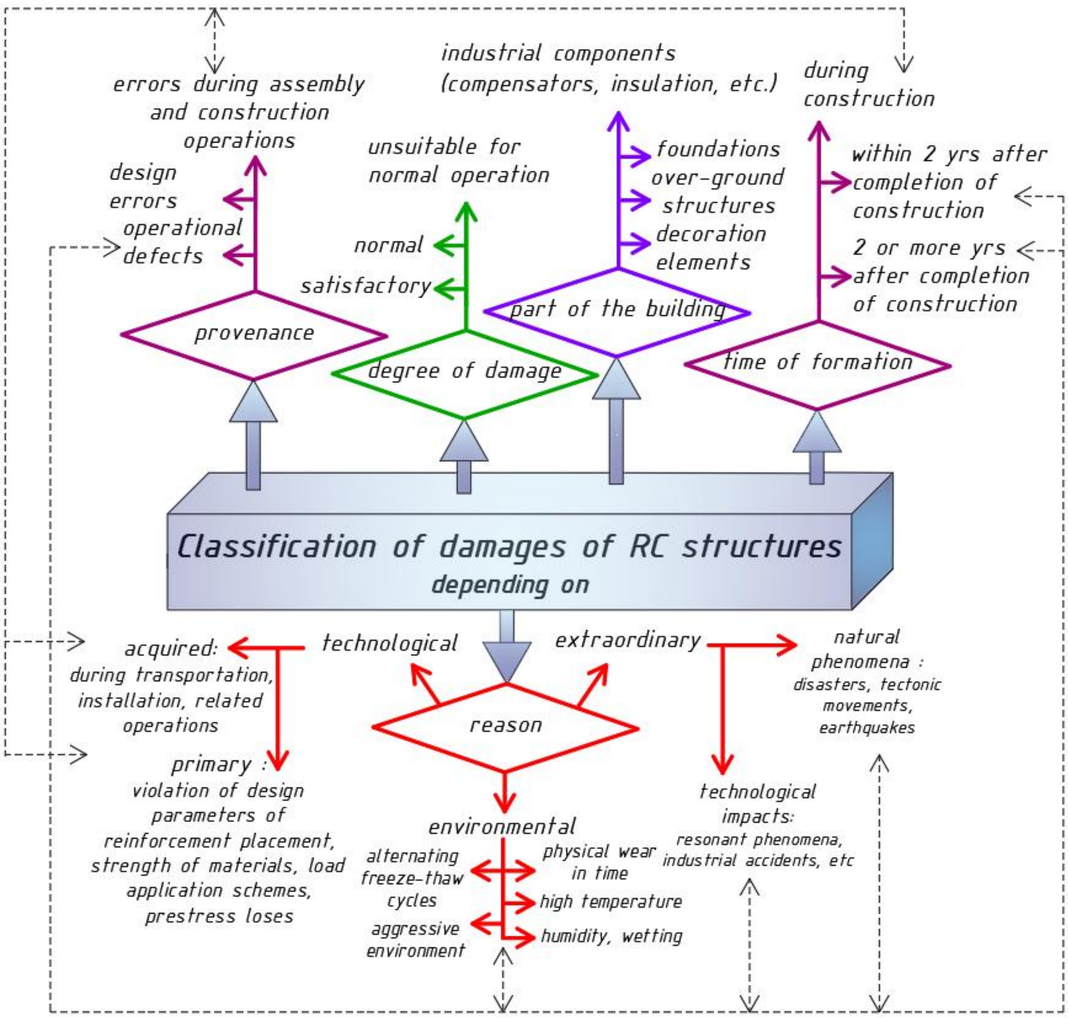

Fig. 1. Classification of damages in RC structures
(Note-Dotted lines indicate logical connections between classification groups)

Currently valid regulations DSTU-N B B.1.2-18:2016 recommend to divide damaged building structures depending on their technical condition into 4 categories: normal, satisfactory, unsuitable for normal operation, emergency.

After detailed review of existing classification concepts for damages in reinforced concrete structures, more complex and compound classification scheme (see Fig. 1).

The issue of deterioration of RC structures complies reliable and objective assessment methods for defects and damages. Thus, the residual load-bearing capacity may be assessed according to the degree of deformability, change in the mechanism of destruction, the accumulation of internal stresses in the material of structures. In addition, the degree of strength deterioration could be assessed on the basis of the energy potential of the structure and changes in its dynamic characteristics (Hait et al., 2018).

Characteristics of the main sources of damage in RC structures

Deterioration or reinforced concrete structural element should be evaluated, taking into account each particular situation and type of negative impact.

Technological influences could be primary (violation of design parameters of reinforcement placement, strength of materials, load application schemes) and acquired (mechanical damage of concrete during transportation and installation, errors during the construction process on the site). In addition, within this group it is necessary to consider prestress losses and their impact on the stress-strain state of reinforced concrete structures (Bossio et al, 2016). Among the environmental causes of damage are physical wear of the building over time, temperature and humidity, aggressive environment, etc. (see Fig. 1). For example, the action of high temperatures on the structure damages the protective layer, reduces the deformation characteristics of concrete and its compressive strength, which could have critical consequences for the structure or building in general (Hibner, 2017; Menz et al., 2021).

The group of extreme influences includes external impacts that were not taken into account by the project: natural phenomena (disasters, tectonic movements, earthquakes) and dynamic technological impacts (resonant phenomena, industrial accidents, etc.).

The great number of research works (Cardone, 2016; Chiu et al., 2019; Lee, 2015) was dedicated to the study of stress-strain state of reinforced concrete structures under seismic influences. Generally, in such extreme situations should be expected the increase of fragility, decrease of deformability and considerable deterioration of reliability of knot connections. In addition, when cyclic character of loading takes place, the fatigue strength of structure could be considerably reduced (Sadeghi et al., 2016).

The influence of aggressive environment is among of the most critical and common causes of damages, which are formed during the operation of the structure. Corrosion defects, which appear in structural element due to this impact should be thoroughly considered and are broadly discussed below.

The problem of the impact of aggressive environments on reinforced concrete structures

Corrosion of reinforcement is one of the critical factors, causing deterioration of the reinforced concrete structure and, consequently, reduction of its expected service life (Blikharskyy Z., et al. 2019; Ferreira, 2006; Kaveh,2019; Mahmoodian, 2020; Ouzaa, 2019; Zacchei, 2021). Great number of studies has been devoted to the analysis of degradation mechanisms in corroded rebar and development of methodic to implement the existing knowledge on this issue (Angst, 2018; Ferreira, 2006; Zacchei, 2021). Preventive numerical approaches for modeling of corrosion processes and subsequent chemical and mechanical parameters are given in the range of scientific studies (Yatsko, 2015; Bhagwat et al, 2020; Dizaj et al., 2021; Blikharskyy Z., et al., 2019).

In general, the corrosion propagation could be considered as the two-stage process, which begins with the stage of initiation, during which the migration of aggressive reagents through concrete to steel and the stage of propagation, associated with the direct accumulation of defects. First, the aggressive substance enters the concrete through pores or cracks, which is accompanied by de-passivation. After that, the corrosion further develops with the speed, depending on the access of oxygen and the level of humidity;

later the corrosion rate increases, the products of chemical transformations are formed, which contributes to the increase of internal stresses. After the corrosion stresses reach the surface layers the cracking and peeling of concrete occurs. The most rapid decrease in the bearing capacity of the reinforced concrete element is observed during the final stage of corrosion, when the cross section of the reinforcement is reduced (Bhagwat et al., 2020).

Reinforcement degradation if often assessed on the basis of diffusion processes in reinforced concrete, which is associated with carbonization and distribution of chloride ions (Chiu et al., 2016; Yatsko, 2015). Chloride-induced corrosion could be described as the time-dependent stochastic function that determines the intensity of cracking in concrete. For instance, Markov chain model directly links visual inspection data with the structural condition of damaged structures, which depends on the state of the interphase surface "reinforcement-concrete" (Dixit, 2021; Dizaj et al., 2021). Corrosion rate is strongly influenced by the amount of corrosion products, which can be used as an input equation for numerical predictive corrosion modeling or as an empirical model to extrapolate experimental test data for further degradation and to interpret initial physical parameters (Gießgen, 2019). The principal scheme, indicating main stages of corrosion is presented on Fig. 2.

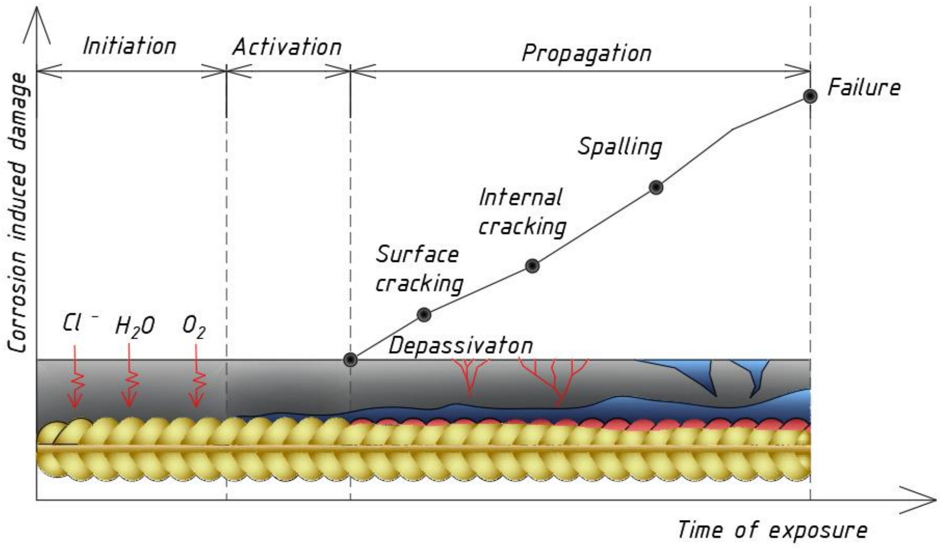

Fig. 2. Principal scheme of corrosion propagation

Corrosion products' volume is 2–6 times greater, than the initial volume of reinforcement, which is the reason of significant tensile stresses in concrete, reduction of tensile strength and ultimate deformations in the protective layer. Therefore, the corrosion process could result in internal stresses, cracks, as well as complex changes in mechanical and chemical properties and structure of adjacent concrete (Gießgen, 2019; Kenny, et al., 2020). Rather promising method of evaluation of structure performance is based on the relationship between the corrosion degree and the width of the cracks` opening in the protective layer (Shakib et al., 2021; Mak et al., 2018). Thus, the width of crack opening could be interpreted as an indicator of the level of corrosion damage in the reinforcing bars and used to accurately determine the term of steel reinforcement depassation. That is, greater crack opening in the protective layer will correspond to the later stages of corrosion initiation.

In addition to the cracking, stresses in concrete, caused by corrosion products, result in the adhesion decrease between reinforcement and concrete. At the later stages of corrosion, the adhesion strength can decrease by up to 70 % and is strongly depends on the diameter of the reinforcing bars and their anchoring. Namely, in order to decrease the corrosion impact on adhesion it could be recommended to use rebar of larger diameter with reliable anchoring (Ben Seghier et al., 2021; Cao et al., 2020). Similarly, authors (Santos et al., 2012) identified two critical consequences of the corrosion process: reduction of the cross section of reinforcing bars and decrease of the adhesion forces between reinforcing bars to adjacent layers of concrete. The adhesion between reinforcement and concrete is the main reason that reinforced concrete exhibits the properties of a composite material, which confirms that the interaction of individual elements of reinforced concrete, as a complex system, requires special attention. It should be noted, that the absence of interaction between the components of the reinforced concrete section, their properties as a synergistic system are lost and the basic design assumptions become unacceptable. It also necessary to take into account losses of prestressing in rebars, subjected to corrosion, which changes the initial stress-strain state of the structure, which was assumed at the design stage (Ponechal, Koteš, et al., 2021).

In the wide range of studies (Dergach et al., 2020; Ciubotariu et al., 2016; Morshed et al., 2020; Nguyen et al., 2021) were highlighted methods for analysis of RC structures` stress-strain state, using accelerated electrochemical methods. Accelerated methods for corrosion modelling (Royani et al., 2020; Santos et al., 2015) in different aggressive environments and at different time intervals indicated the significant decrease in the plasticity and deformability characteristics of specimens exposed to aggressive environments. As the corroded structures are suspected to brittle fracture mechanism, it could be recommended to use reinforcement with greater limit strain. In addition, the effect of corrosion on torsional strength should be noted Thus, at the level of damage of about 20 %, there is the reduction of the maximum torque of the reinforced concrete section by half (Santos et al., 2012; Santos et al., 2021).

At the later stages of corrosion shear capacity as well as the stiffness of reinforced concrete bended elements decreases and is in correlation with the width of the cracks` opening, caused by reinforcement corrosion (Xia et al., 2012). In addition, authors (Xia et al., 2012) emphasize the danger of transition to fragile destruction mechanisms, as well as the destruction of structures due to violation of the anchoring of transverse reinforcement.

One of the most reliable approaches to evaluate the residual load-bearing capacity of RC structures is based on the combination of numerical methods and field observations of real damages (Koteš et al., 2021). Visual observation in combination with non-destructive methods of assessing the strength of materials provide a thorough idea of the stress-strain state of the building or structure. Therefore, numerical modeling helps to reliably estimate residual strength and predict further degradation mechanisms. Thus, when using the results of non-destructive testing of the structure as input data for the finite element model, we obtain the detailed idea of the reliability level of the structure, taking into account the time factor and spatial variability of strength characteristics (Dixit et al., 2021).

There are the variety of practical method for detecting corrosion of reinforcing steel, among which the following should be indicated: electrochemical measurements and methods based on the correlation of digital images. Also, additionally could be recommended the latest analytical technologies of defectoscopy, which demonstrate high efficiency and accuracy: micro-X-ray diffraction, energy-dispersion and electrochemical spectroscopy, methods of acoustic emission and thermography, etc (Ebell et al., 2018; Zhu et al., 2013; Dixit et al., 2021).

The number of works were dedicated to the analysis of different corrosion propagation mechanisms (Akpanyung et al., 2019; Li et al., 2019; Linwen et al., 2015). In general, corrosion could be divided into uniform (general) and local (pitting) corrosion. Pitting corrosion is a specific, localized form that occurs in small areas and can have a significant impact on the reliability of the structure. The mechanisms of destruction in local and uniform corrosion are fundamentally different. Thus, pitting corrosion causes sharper decrease in the bearing capacity of the reinforced concrete element and the tendency to brittle failure. Pitting corrosion should be considered, taking into account its degree of heterogeneity, described by the pitting factor (the ratio of the greatest depth of destruction to its average value).

Conclusions

On the basis of conducted thorough research and literature review, it could be concluded, that deterioration of RC structures is complex issue, which should be considered with the account of various factors. Damages and defects should be assessed, according to different criteria, including the degradation degree, type, time and cause of formation, etc. In the article the detailed analysis of main causes of RC structures is conducted and subsequent classification scheme is proposed. Also, as the corrosion is nowadays the most critical reason of decrease of load-bearing capacity, this issue is discussed in more detail. Further theoretical and experimental research, as well as field surveys are necessary and could greatly contribute to the problem of defects and damages in RC structures and deepen the understanding of damaged RC structure behavior.

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АНАЛІЗ НАЙПОШИРЕНІШИХ ПОШКОДЖЕНЬ І ДЕФЕКТІВ У ЗАЛІЗОБЕТОННИХ КОНСТРУКЦІЯХ: ОГЛЯД

Залізобетонні конструкції сьогодні є одними із найпоширеніших як в новому будівництві, так і в наявних будівлях і спорудах. Вони часто зазнають різних негативних впливів навколишнього середовища, що знижує їхню надійність і довговічність. Оптимізація будівельних конструкцій передбачає продовження їх життєвого циклу, оцінку їх довговічності, надійності та залишкового терміну служби. Для цього необхідна достовірна оцінка наявних пошкоджень, що є наслідком негативного впливу навколишнього середовища. Дефекти і пошкодження у залізобетонних конструкціях є складним питанням, яке необхідно розглядати з урахуванням різних факторів. Пошкодження та дефекти слід оцінювати за різними критеріями, зокрема за ступенем деградації, типом, часом та причиною утворення тощо. У статті детально проаналізовано найпоширеніші пошкодження залізобетонних конструкцій на основі ретельного огляду літератури з цього питання. Також запропоновано класифікацію причин зниження несучої здатності залізобетонних конструкцій. Виділено основні аспекти, які необхідно враховувати під час оцінювання залишкового ресурсу залізобетонних конструкцій за різних видів пошкоджень і дефектів. У дослідженні додатково розглянуто механізми корозії та особливості змін напружено-деформованого стану залізобетонних елементів в умовах корозійного впливу. Вивчення залізобетонних конструкцій за наявності в них пошкоджень і дефектів різних типів можливе лише за умови розуміння їхньої поведінки і структурних особливостей. Подальше теоретичне й експериментальне дослідження проблеми дефектів у залізобетонних конструкціях у комплексі з польовими дослідженнями реальних об'єктів необхідне для розроблення достовірних методів оцінювання їхньої залишкової несучої здатності.

Ключові слова: залізобетонні конструкції; пошкодження; довговічність; залишкова несуча здатність; корозія.