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OVERVIEW OF DAMAGE FACTORS OF REINFORCED CONCRETE STRUCTURES AND THEIR IMPACT ON LOAD-BEARING CAPACITY

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This review analyzes key factors contributing to damage in reinforced concrete (RC) structures, including reinforcement corrosion, chemical attacks, cyclic and long-term mechanical loads, and extreme temperature effects. The study highlights crack formation as a primary damage mechanism, leading to structural degradation. Advanced computational modeling techniques, such as finite element analysis, offer valuable insights into crack propagation and corrosion processes but require further refinement. Future research should focus on developing high-performance materials, improving corrosion protection methods, and refining predictive models. Additionally, sustainable rehabilitation techniques and experimental validation of damage mechanisms are essential for enhancing the durability and serviceability of RC structures.

Keywords: Reinforced concrete (RC) structures, cracking, corrosion, loading, load-bearing capacity, durability.

Introduction

Reinforced concrete (RC) structures are widely used in construction due to their strength, durability, and versatility. However, over time, these structures are subject to various damaging factors that can reduce their load-bearing capacity, affecting their safety and longevity. The performance of RC structures is influenced by a multitude of factors, including mechanical stresses, environmental influences, and material degradation. Corrosion of reinforcement, thermal effects, and aggressive chemical attacks are some of the leading causes of damage that contribute to the deterioration of these structures.

In addition to physical and environmental factors, poor design, inadequate construction practices, and insufficient maintenance can exacerbate the damage to RC structures. These factors often lead to cracks, spalling, and, in extreme cases, catastrophic failure of structural components. As these issues evolve over time, it becomes increasingly important to assess and understand the causes of damage and the subsequent loss of load-bearing capacity.

This review aims to provide an in-depth analysis of the primary factors contributing to the damage and degradation of RC structures, while also highlighting recent advancements in research and innovative methods for assessing and preventing such damage. Emphasizing the need for proactive measures in the design and maintenance of RC structures, the study presents a comprehensive understanding of how various external and internal influences contribute to the failure mechanisms of reinforced concrete.

Given the widespread use of reinforced concrete in infrastructure, from bridges and buildings to dams and tunnels, understanding the mechanisms behind structural damage is crucial for improving the sustainability and safety of existing and future constructions. The findings of this review underscore the need for continued research and development of diagnostic techniques, materials, and preservation strategies to mitigate the risks associated with damage to RC structures. Furthermore, the insights gained from this analysis are integral to optimizing structural design, maintenance protocols, and rehabilitation efforts, ensuring that RC structures can withstand both environmental and mechanical challenges over their operational lifespan.

Materials and methods

In modern construction of buildings and structures, the predominant share belongs to the use of reinforced concrete (RC) structures (Bobalo et al., 2019; Verma et al., 2014). RC plays a crucial role in fully utilizing strength indicators, creating various forms, ensuring fire resistance, durability, and economic efficiency. The use of RC allows for the creation of structures with high load-bearing capacity, capable of withstanding significant external loads (Vatulia et al., 2014). Over time, improvements in RC have made it a universal material for various construction applications and the implementation of different structural types.

RC owes its versatility to the synergy of its constituent materials: concrete withstands compressive loads, while steel reinforcement resists tensile stresses, both as working and structural reinforcement (Karpiuk et al., 2020). The first proposal to combine concrete with metal elements was made by French gardener Joseph Monier in the late 19th century to create garden pipes and planters (Meier, 1995). Over time, the idea of integrating these materials into a single system RC was rapidly adopted in bridge, building, and infrastructure construction (Meier, 1995). In 1886, François Hennebique first applied RC for constructing buildings and structures, and his innovative design approaches enabled the achievement of high-performance characteristics (Meier, 1995).

With each decade, research into the mechanical properties and behavior of RC under loads has increased significantly, leading to improved design and construction methods (Triantafillou, 1998). A crucial aspect today is the reliability and durability of RC structures, which can only be ensured through proper technical supervision and timely restoration work (Blikharskyy, 2021). High fire and corrosion resistance provide an additional level of safety and longevity for structures (Broomfield, 2007). The use of RC reduces construction costs, while innovative supplementary materials and advanced manufacturing technologies further enhance strength properties (Oehlers, 2004; Broomfield, 2007).

Modern research in the development of new materials and technologies, such as fiber-reinforced concrete, nanotechnologies, and polymer-based materials, opens new prospects for the modernization of RC structures, enhancing their strength, resistance to aggressive environments, and overall durability (Meier, 1995).

Over time, RC structures are subject to various types of damage and defects, potentially leading to failure under poor operational conditions (Bobalo et al., 2019). Damage primarily arises due to prolonged service life under mechanical and technological stresses, as well as exposure to aggressive environments (Rezaie et al., 2020; Klymenko & Polyanskyi, 2019).

Such damage and defects in RC structures reduce their load-bearing capacity, leading to reliability issues and decreased durability (Voskobiinyk, 2010; Chiu et al., 2019). Early detection and repair of damages are critical for ensuring the longevity of structures (Bazant, 1998). Research by Bastidas and (Bastidas, 2020) provides a detailed classification of damages and defects in RC structures caused by various factors. One such classification highlights technological influences, which include poor adherence to construction tolerances, improper concreting practices, violations of assembly requirements, and issues related to transportation and on-site installation (Blikharskyy & Kopiika, 2019).

One of the most common deficiencies is inadequate protective layer thickness, inaccuracies in geometric dimensions, and deviations in the physical and mechanical properties of materials (Blikharskyy, 2019; Blikharskyy, 2020).

The classification of damage is also addressed in regulatory engineering practices in Ukraine DSTU-N B V.1.2-18:2016 “Guidelines for the inspection of buildings and structures to determine and assess their technical condition” and in the European standard DCC-104 RILEM (Rilem Technical Committees, 1991). The effect of aggressive environments on concrete and reinforcement has been the focus of multiple studies, particularly in terms of damage occurring both in the zone of maximum moment and across the entire cross-section (Fu et al., 2017; Smith, 2007). Structures in the chemical industry are particularly susceptible to such damage due to the high concentration of compounds that degrade RC.

A key observation made by various researchers is the gradual reduction in load-bearing capacity with increasing corrosion levels. Specifically on (Blikharskyy, 2005) focuses on studying corrosion processes under simultaneous loading conditions and evaluating changes in the stress-strain state of RC structures under these conditions. In modern construction research, corrosion in RC structures remains a highly relevant issue. The primary consequences of corrosion include a reduction in the cross-sectional area of the steel reinforcement and damage to the compressed concrete zone. Such deterioration leads to an abrupt decline in the physical and mechanical properties of materials. Studies conducted by both Ukrainian and international researchers have provided assessments of the impact of corrosion damage on the actual load-bearing capacity of RC structures (Bastidas-Arteaga et al., 2009; Savitskyi, 2003; Mahmoodian, 2020).

The most destructive phase of corrosion occurs when reinforcement is exposed (Ye, 2013). This process follows a two-stage sequence: initially, aggressive substances (compounds) and air migrate through the pores and cracks in the concrete, reaching the steel reinforcement (Zhao et al., 2023; James et al., 2019; Angst, 2018). The next stage involves an active chemical corrosion process, during which corrosion products are formed on the reinforcement surface. The presence of moisture, oxygen, and various chemical compounds accelerates corrosion, leading to a reduction in the reinforcement's cross-sectional area (Malumbela et al., 2010; Xu et al., 2018).

Corrosion significantly impacts the load-bearing capacity of RC beams, particularly when the reinforcement cross-section decreases due to corrosion, as demonstrated in research by (Torres-Acosta et al., 2007). Corrosion processes have been examined in greater detail in studies by (Angst, 2018; Otieno et al., 2011), while the propagation of corrosion in crack zones is explored in (Lin, 1990).

A particularly important research area involves assessing the influence of corrosion on the stress-strain state of RC structures. Studies by (Yuan et al., 2024; Peng et al., 2024) suggest that one of the most effective solutions to this issue is the use of special concrete additives to enhance the necessary physical and mechanical properties. For example, (Song et al., 2019) developed a superhydrophobic concrete (S-concrete) coating with a sliding angle of $6.5 \pm 0.5°$ and a contact angle of $160 \pm 1°$. This coating provides high mechanical strength at a low cost while maintaining superhydrophobic properties even after scratching or abrasion. Moreover, S-concrete demonstrates excellent anti-icing properties and high corrosion resistance, making it practical for use in specific regions.

Another research direction involves establishing the relationship between corrosion levels and crack formation in RC structures, as cracking is a critical factor in the corrosion process of reinforcement bars (Corral-Higuera et al., 2011; Mundra et al., 2017). In a study by (Fursa et al., 2017), a promising method for assessing corrosion damage was proposed, where the primary indicator of corrosion intensity is the width of cracks.

Since RC consists of two materials (concrete and steel), their joint performance is crucial and depends on the bond between them. Corrosion weakens this bond, ultimately reducing the overall load-bearing capacity of the structure (Gu et al., 2018). The contact between concrete and reinforcement plays a vital role in ensuring proper adhesion. A study by (Chen et al., 2019) examined the effects of key concrete design parameters including the water-to-cement ratio, concrete cover thickness, and aggregate size on the microstructure of the reinforcement-concrete interface.

Corrosion of reinforcement and concrete leads to crack formation, and in advanced stages, it can cause spalling of concrete layers. This is considered one of the most critical damage types due to its negative impact on the stress-strain state of RC structures (Chrysafi et al., 2017; Pozzer et al., 2021). Cracks in RC structures arise not only over time due to loading but also from various other factors. They may originate during the manufacturing stage or develop during operation. The primary causes include improperly designed reinforcement frameworks, insufficient concrete cover, excessive prestressing force, technological influences, shrinkage deformations, as well as environmental and thermal effects (Patel and Peralta, 2017).

A study by (Khiem and Toan, 2014) derived a Rayleigh coefficient considering an arbitrary number of cracks and developed a simplified sequential tool for modal analysis of cracked structures. Other studies (Ercolani et al., 2018; Khiem and Toan, 2014) highlight that the key parameter governing stress redistribution in structures is crack width. Numerical modeling of cracks in software systems has made it possible to predict crack formation and its impact on the stress-strain state of RC structures (Cohen et al., 2018; Kwan and Ma, 2016). In another study (Nuguzhinov et al., 2020), analytical expressions were obtained to determine the external bending moment and pre-stresses at which normal cracks form perpendicular to the axis. This allows for assessing the load-bearing capacity of RC structures at the design stage according to both limit state groups and evaluating their actual technical condition in service.

Research on the residual load-bearing capacity of RC beams with existing damage has been explored in various studies. Experimental results indicate that the deformation behavior of flexural elements is highly dependent on defects and damage, particularly in the compressed concrete zone. Damage in this region leads to a reduction in the ultimate strain of concrete and causes a shift in the neutral axis (Klymenko and Polyanskyi, 2019).

RC structures subjected to bending experience significant loads during operation. Special attention is given to damage in the compressed concrete zone, as defects in this region can lead to serious structural problems and a reduction in overall load-bearing capacity. The primary factors affecting damage in the compressed zone include technological influences, mechanical loads, aggressive environments, and chemical factors.

Mechanical loads, particularly long-term loading, are among the most common causes of damage to the compressed concrete zone in flexural RC structures. Research by (Bazant, 1998) indicates that sustained loading causes concrete creep, leading to microcrack formation and a reduction in the strength of the compressed concrete fibers. Cyclic loading accelerates material fatigue, resulting in progressive microcracking and initiating a stepwise deterioration process in concrete (Fatemi and Yang, 1998).

Developed (Golos and Ellyin, 1987) a method that incorporates both crack initiation and propagation stages. Their damage criterion is based on the concept of cumulative strain energy density as a key damage parameter. The effect of mean stress on damage accumulation is also incorporated into this formulation. Furthermore, the influence of loading sequence was investigated using a novel testing setup that enables precise control over stress states and fracture zones. Their stepwise deformation modeling approach accounts for load sequence effects, predicting fatigue life and the complete evolution of deformation under cyclic loading.

Aggressive environments, particularly the presence of sulfates, chlorides, and acids, significantly impact the condition of the compressed concrete zone. Corrosion of reinforcement due to chloride penetration or carbonation-induced deterioration leads to crack formation in concrete, reducing its strength (Broomfield, 2007). This study presents an innovative poromechanics based model for analyzing concrete subjected to low temperatures, incorporating nanoscale length-scale effects and a comprehensive review of alkali-aggregate reaction modeling in concrete.

Another major environmental factor affecting RC structures is freeze-thaw cycles, which contribute significantly to concrete degradation. Developed (Fagerlund, 1977) found that these cycles induce microcracks in concrete, leading to its progressive deterioration. To mitigate this issue, additional admixtures should be incorporated into concrete during manufacturing, especially for structures exposed to open environmental conditions.

Chemical agents such as sulfates and acids contribute to the chemical degradation of concrete. Sulfate penetration into the concrete pores and depth leads to the formation of ettringite, which initially causes expansion and, over time, results in the destruction of the compressed concrete zone (Gollop and Taylor, 1992; Santhanam and Cohen, 2002). Investigated key aspects of sulfate attack on concrete and proposed monitoring methods along with modeling criteria for sulfate-induced damage (Santhanam and Cohen, 2002). Acid exposure also negatively affects RC structures by dissolving the cement matrix, which accelerates crack formation and expansion in concrete (Taylor et al., 2001).

A reduction in the load-bearing capacity of RC structures also occurs due to temperature effects, whether excessively high or low (Hibner, 2017). In fire conditions, concrete suffers damage to its protective layer, leading to a decrease in overall strength and deformation parameters (Broomfield, 2007). Temperature fluctuations induce thermal expansion and contraction of concrete, causing thermal cracking. High temperatures, in particular, contribute to the degradation of concrete structure and a reduction in structural load-bearing capacity (Hlavička et al., 2024; Zhou et al., 2024).

Examined the effect of temperature on concrete spalling and provided recent findings suggesting that spalling should not occur under certain conditions, emphasizing the need to account for it during structural design (Hager, 2013). Fire-induced concrete spalling damages the cross-section and significantly reduces the structural load-bearing capacity.

Nowadays, computational modeling is widely used to study damage in RC structures. Employed non-traditional finite element methods to model fiber-reinforced RC beam-columns (Wang et al., 2013). The study demonstrated that modeling allows for predicting the formation and progression of microcracks in concrete. Developed (Lee et al., 2016) a simulation program for chloride attack, incorporating a two-dimensional finite element method to predict chloride ion penetration. Each discretized element in the finite element model was treated as an independent object capable of storing necessary parameters and autonomously calculating chloride content values, facilitating the simulation of failure in critical regions. The findings indicate that the deterioration of reinforcement due to corrosion in RC structures is significantly influenced not only by the damaged concrete but also by the structural geometry, which plays a crucial role in the overall degradation process.

Results and discussion

The analysis of damage mechanisms in reinforced concrete (RC) structures highlights the significant impact of various physical, chemical, and mechanical factors on their durability and load-bearing capacity. Corrosion of reinforcement and concrete degradation due to environmental exposure lead to progressive cracking, spalling, and ultimately structural failure. Among the primary causes, improper reinforcement design, inadequate concrete cover, excessive pre-stressing forces, and technological defects during construction contribute to early damage initiation. Moreover, shrinkage-induced deformations, atmospheric and temperature influences further exacerbate the degradation of RC structures over time.

One of the most critical aspects affecting structural integrity is the formation and propagation of cracks, which not only weaken the structure but also serve as pathways for aggressive agents such as chlorides, sulfates, and carbon dioxide. These chemical agents penetrate the concrete matrix, triggering reinforcement corrosion and causing expansive reactions, such as ettringite formation, which lead to further deterioration. Additionally, exposure to cyclic loading induces fatigue-related microcracks, progressively reducing the structure’s strength. Long-term mechanical loads contribute to creep deformations, affecting the stiffness and serviceability of RC elements.

Fire exposure and extreme temperature variations also have a profound impact on the stability of RC structures. At elevated temperatures, concrete undergoes thermal expansion, spalling, and degradation of its mechanical properties, leading to a significant reduction in load-bearing capacity. Cold-weather conditions, particularly freeze-thaw cycles, accelerate crack formation and contribute to concrete disintegration. This necessitates further exploration of advanced concrete mixtures incorporating supplementary cementitious materials and chemical admixtures to improve resistance against thermal effects and environmental degradation.

Computational modeling has proven to be an essential tool for predicting damage evolution in RC structures. Advanced finite element models allow for the simulation of crack initiation, chloride penetration, and fatigue damage progression, providing a valuable framework for assessing structural reliability. However, existing models require further refinement to incorporate multi-scale deterioration mechanisms, including nanomechanical interactions and microstructural changes in concrete due to aggressive environments.

Conclusions

Given the extensive damage mechanisms identified in RC structures, future research should focus on:

1. Development of advanced materials – investigating high-performance concrete mixtures with self-healing properties, fiber reinforcement, and nano-additives to enhance resistance against chemical and mechanical degradation.

2. Enhanced corrosion protection strategies – implementing innovative protective coatings, cathodic protection methods, and chloride-resistant reinforcement materials to extend the service life of RC structures.

3. Refinement of computational models – developing multi-scale numerical models that integrate deterioration kinetics, chemical diffusion processes, and mechanical damage evolution to improve predictive accuracy.

4. Experimental validation of damage mechanisms – conducting large-scale laboratory and field tests to analyze the long-term behavior of RC structures under real-world loading and environmental conditions.

5. Sustainable rehabilitation techniques – exploring eco-friendly restoration methods, such as bio-based repair materials and low-carbon cement alternatives, to minimize environmental impact while enhancing structural resilience.

By addressing these critical research gaps, future advancements in material science, structural engineering, and computational modeling will contribute to the development of more durable and sustainable RC structures capable of withstanding complex environmental and mechanical stressors.

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ОГЛЯД ФАКТОРІВ ПОШКОДЖЕННЯ ЗАЛІЗОБЕТОННИХ КОНСТРУКЦІЙ ТА ЇХ ВПЛИВ НА НЕСУЧУ ЗДАТНІСТЬ

Залізобетонні конструкції зазнають впливу численних факторів пошкодження, що безпосередньо впливають на їхню несучу здатність і довговічність. Основними причинами пошкоджень є корозія арматури, тріщиноутворення, механічні навантаження, вплив агресивного середовища, температурні коливання та довготривалі експлуатаційні процеси. Корозія арматури, спричинена проникненням хлоридів або карбонізацією, призводить до тріщин і руйнування бетонного прошарку, що змінює напружено-деформований стан конструкцій. Циклічні навантаження та повзучість бетону зумовлюють поступову деградацію матеріалу та виникнення мікротріщин, що в довгостроковій перспективі знижує несучу здатність конструкцій. Додатково негативно впливають агресивні середовища, зокрема сульфатна і кислотна атаки, які спричиняють хімічну корозію бетону, що зрештою порушує його структуру. Унаслідок високих температур, особливо під час пожежі, бетон втрачає міцність через руйнування його мікроструктури та спонтанне відколювання. Аналіз сучасних досліджень показує, що комп’ютерне моделювання пошкоджень – ефективний інструмент для прогнозування процесів деградації та для розроблення підходів до їх мінімізації. Визначено, що використання методів кінцевих елементів дає змогу враховувати широкий спектр чинників та точно оцінювати вплив пошкоджень на стан конструкцій. У статті наведено огляд основних механізмів та причин руйнування залізобетонних конструкцій та їхнього впливу на несучу здатність, що допомагає краще розуміти й оцінювати процеси, що відбуваються у матеріалах під дією експлуатаційних навантажень. Результати досліджень можуть бути використані для вдосконалення методів проєктування та розроблення ефективних стратегій (технологій) для підсилення, відновлення і ремонту залізобетонних конструкцій.

Ключові слова: залізобетонні (RC) конструкції, тріщини, корозія, навантаження, несуча здатність, довговічність.