

## Review

# An Overview of the Main Types of Damage and the Retrofitting of Reinforced Concrete Bridges

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**Abstract:** Restoring and strengthening existing bridges is more economically and environmentally feasible, as cement production in new RC bridges significantly contributes to CO<sub>2</sub> emissions. Additionally, the production of composite carbon materials for strengthening RC structures does not require a large amount of energy, unlike the production of steel for reinforcement, which requires a significant amount of electricity and, accordingly, causes a significant amount of CO<sub>2</sub> emissions. This is why this article presents a comprehensive review of the damage, calculations, and strengthening of RC bridge structures. It examines the main types of damage, including mechanical impacts, material fatigue, corrosion processes, seismic actions, and thermal loads. The mechanisms of their formation, correlations with environmental factors, and operational conditions are detailed. Examples of damage from real engineering objects are provided to assess the scale of the problem. Approaches to the calculation of RC bridge structures are analyzed, particularly methods for modeling the stress–strain state, considering crack formation and material degradation. Key studies by Ukrainian and foreign researchers are highlighted, identifying areas for further methodological improvement. Special attention is given to traditional and modern strengthening methods, including the use of steel elements, composites, and carbon strips. A comparative analysis of the effectiveness of different strengthening approaches is conducted. The conclusion emphasizes the need for further development of existing diagnostic, calculation, and strengthening methods. The integration of innovative materials and technologies is particularly relevant for enhancing the durability of bridges under modern operational loads.

**Keywords:** concrete; RC structures; damage; load-bearing capacity; strengthening; composite materials; bridge constructions; environmental protection; reduction of CO<sub>2</sub> emissions



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## 1. Introduction

Reinforced concrete (RC) bridge structures form the backbone of the modern world's transportation infrastructure, connecting cities, regions, and countries. Their unique ability to withstand significant loads and long-term operation makes them critical for economic and social development. However, over time, under the influence of natural phenomena

and operational loads, RC bridges gradually lose their functionality and safety. This necessitates the constant analysis of their condition, the improvement of calculation methods, and the implementation of effective restoration and strengthening technologies [1–3].

Strengthening existing reinforced concrete bridges is a more environmentally friendly option. When manufacturing new reinforced concrete structures, the production of cement as the main component of concrete and steel for reinforcements causes a significant amount of CO<sub>2</sub> emissions and environmental pollution. That is why a more environmentally friendly option is the restoration of existing reinforced concrete bridges. The work also considers the strengthening of reinforced concrete bridge structures using carbon composite materials, since the production of reinforced steel requires a large amount of electricity and causes significant CO<sub>2</sub> emissions. Moreover, composite materials based on carbon fibers are not associated with the use of large-capacity energy sources, which saves the environment and significantly reduces CO<sub>2</sub> emissions during the manufacturing process. CFRP manufacturing reduces CO<sub>2</sub> emissions compared to steel by eliminating fossil fuel-based smelting, requiring less energy-intensive processing, and using significantly less material due to its high strength-to-weight ratio. Additionally, its lightweight nature lowers transportation emissions, extends product lifespan with minimal maintenance, and enables recycling, further reducing its environmental impact.

One of the key challenges faced by RC bridges is damage caused by external factors, such as reinforcement corrosion, freeze–thaw cycles, chemical aggression, and dynamic loads from traffic [4]. For instance, reinforcement corrosion is the most common cause of reduced structural strength. In many cases, it is triggered by chloride penetration or carbonation of concrete, making the steel reinforcement susceptible to corrosive processes. In regions with harsh climates, temperature fluctuations further exacerbate the problem, leading to crack formation in the concrete and a weakening of its bond with the reinforcement.

In addition to natural factors, mechanical influences play a significant role. Material fatigue, caused by repeated cyclic loading, leads to the accumulation of microcracks and the gradual degradation of both concrete and reinforcement. Overloading bridges with heavy-duty vehicles or impact loads resulting from accidents or natural disasters also contributes to the destruction of load-bearing elements. In seismically active regions, earthquakes introduce significant dynamic loads that exceed the design strength of the structures, adding to the risks.

The economic and environmental consequences of the failure of bridge structures underscore the importance of timely intervention. Restoring damaged areas of RC bridges is a critical task that requires a comprehensive approach. Traditional strengthening methods, such as concrete jacketing, have been used for decades [5]. However, modern technologies, including composite materials, ultra-high-performance concrete (UHPC), and digital monitoring systems, offer new possibilities for enhancing the durability of these structures [6].

The calculation and analysis of bridge conditions have also evolved significantly. While earlier methods were based on classical statics, today, computer models, particularly the finite element method (FEM), are widely employed [7]. This approach allows for the evaluation of the nonlinear behavior of materials, the consideration of dynamic impacts, and the prediction of the long-term stability of structures.

This article focuses on the analysis of key aspects of damage, strengthening, and the calculation of RC bridge structures. Particular attention is paid to modern materials and technologies that enable a more effective assessment of structural conditions and the restoration of their functionality. The aim is to summarize existing research and methods to ensure the long-term reliability of bridge structures.

## 2. Causes and Consequences of Damage to Reinforced Concrete Bridge Structures

### 2.1. Mechanical and Dynamic Loads Impacts on RC Bridges

RC bridge structures are subjected to various mechanical impacts during their service life, which can lead to damage. Mechanical damage often results from external factors such as vehicle collisions, heavy falling objects, or impacts from moving elements, such as barges during floods. Localized mechanical damage is most frequently observed in beams, deck slabs, or bridge supports, particularly in areas with high traffic intensity [8].

One of the primary mechanisms of damage is structural deformation. Excessive loads can cause cracking in concrete elements. Dynamic impacts, such as traffic movement or seismic vibrations, play a significant role in mechanical damage. These loads can be much greater than static ones, requiring careful consideration during the design and operation of bridges [9–11]. Under dynamic loads, not only the magnitude, but also the frequency of the impact, is critical. Studies have shown that cyclic loading causes the accumulation of microcracks, which eventually leads to the fatigue failure of concrete structures [12,13]. This damage is especially evident in the support zones of bridges, where maximum deformations occur [14].

Dynamic loads, particularly those caused by the movement of heavy trucks, contribute to crack formation in areas of high stress, such as the zones supporting bridge spans. If timely monitoring and strengthening measures are not taken, these cracks can result in significant structural problems. Bridges with high traffic intensity are at a greater risk of developing fatigue cracks, especially if they do not undergo regular technical inspections [15,16].

Traffic-induced dynamic loads, including braking and acceleration forces, create localized stress concentrations in concrete. This can lead to cracking, particularly in compression or tension zones. Additionally, high-speed traffic generates vibrations that gradually weaken the structure over time [17].

Seismic impacts are a major cause of bridge damage, especially in earthquake-prone regions. During earthquakes, bridge structures are subjected to significant horizontal and vertical vibrations. Dynamic loads from seismic activity can cause severe cracking in compressed and tensioned concrete zones and disrupt connections between structural elements. Bridges that are not designed to withstand seismic forces may suffer substantial damage even during moderate earthquakes. The high seismic forces often result in severe cracking, the displacement of structural components, and even the breakage of reinforcement bars [18].

Seismic loads are challenging to model due to their unpredictability and heterogeneity. Determining the exact impacts of earthquakes on various types of structures is a critical aspect of research, including calculations and modeling under seismic conditions. Common seismic damage includes the deformation of supports and delamination of reinforcement from the concrete shell. This is particularly evident in bridges located in regions with high seismic activity, where structures are often under stress and vulnerable to earthquake-induced failures. Researchers highlight insufficient seismic isolation and outdated design solutions as the primary factors contributing to such damage [19].

### 2.2. Impact of Aggressive Environments on Bridge Structures

Beyond primary damage mechanisms like corrosion (Figure 1), dynamic loads, and thermal effects, other factors also contribute to the degradation of bridge structures. One such factor is high traffic intensity. Bridges located on major transportation routes are significantly affected by the continuous movement of freight and passenger vehicles. This can lead to structural overloading, causing fatigue damage and material wear.

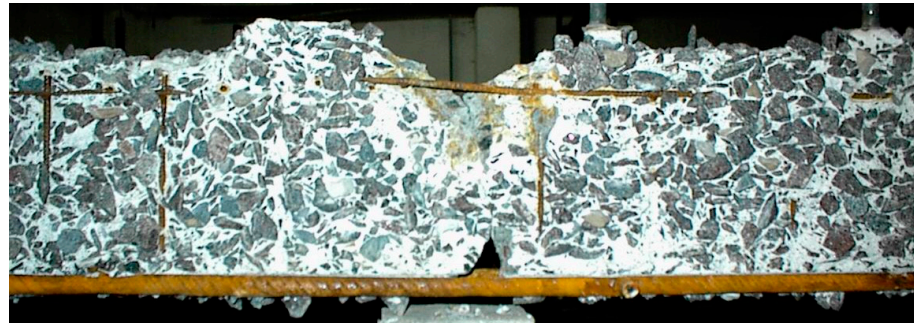


**Figure 1.** An example of the corrosion of reinforced concrete structures (authors' own research).

This section emphasizes the importance of addressing mechanical impacts on RC bridge structures through improved monitoring, the accurate modeling of dynamic and seismic loads, and the implementation of advanced strengthening techniques to ensure their long-term functionality and safety.

Corrosion in reinforced concrete structures can lead to catastrophic consequences, as exemplified by the collapse of the Dresden Bridge (Figure 2). The collapse of Dresden's Carola Bridge was primarily attributed to hydrogen-induced stress corrosion cracking. This phenomenon led to the deterioration of critical structural components, compromising the bridge's integrity and ultimately resulting in its failure [20].



**Figure 2.** The collapse of the Dresden Bridge (authors' own photo).

Overloading is one of the most common causes of damage to bridge structures. It can result both from the overloading of vehicles and from changes in bridge operating conditions when they are subjected to heavier loads than those considered at the design stage. Modern transportation, which significantly exceeds the design load-bearing standards of bridges, is the main source of overloading. As a result, deflections, plastic deformations, and cracks in load-bearing elements occur. Especially critical are bridges built 30–40 years ago when traffic volumes were much lower [21].

Overloading can cause structural deformations such as deflections or cracks, as well as deformations in supports, which are critical for bridge safety. Increased traffic intensity and the frequent overloading of bridges lead to fatigue cracks in reinforcement and concrete, significantly reducing the strength of structures and requiring their reinforcement. Overloading can also deform the bridge deck, subsequently damaging joints and causing material delamination. Numerous cases exist where overloading by trucks has led to serious damage, particularly in the areas of suspension beams or supports. This is especially significant for older bridges where the consideration of overloading may not have been included in the original design [22].

The fatigue process of materials is critical for RC structures, particularly when bridge structures are subjected to cyclic loads, as it is one of the main mechanisms causing damage during their operation. Under cyclic loads, even when each load does not exceed permissible limits, the constant impact of loads can accumulate damage in the material, particularly in reinforcement and concrete. The fatigue of materials caused by repeated cyclic loads is another significant cause of damage. Load cycles caused by traffic lead to microcracks in the concrete. Over time, these cracks develop, reducing the load-bearing capacity of structures. This is particularly the case for bridges with high traffic intensity, where material fatigue can manifest within 10–15 years of operation [23].

Dynamic loads, such as traffic movement or seismic vibrations, often lead to fatigue cracks that initially appear as microcracks but over time can result in severe structural damage. This effect is typically evident in structures subjected to dynamic loads, such as highway or railway bridges, where vehicle movements cause constant vibrations. It should be noted that cyclic loads from heavy trucks can cause fatigue failures in the material even in areas where no obvious damage from static loads is visible. Additionally, this can lead to the fatigue deformation of metal elements, reducing their strength.

Other mechanical damage includes impacts that may result from vehicle accidents or the effects of heavy loads [24]. For example, impact loads from moving vehicles, such as heavy trucks, can cause local deformations in structures, leading to cracks or even damage in areas of maximum stress. Studies have shown that even minor cracks caused by mechanical damage can significantly reduce the load-bearing capacity of a bridge. This is because cracks often act as entry points for moisture and aggressive chemicals, accelerating corrosion processes.

Bridges can also be damaged due to impact loads, which may occur during vehicle collisions, floods, or the displacement of large natural objects such as rocks or trees. An impact can result in localized cracks in the concrete or even structural displacement. One of the most serious types of impact damage occurs during collisions with vehicles, typically heavy trucks. Such damage is particularly noticeable in bridge supports and suspension elements [25]. For example, accidents and collisions involving bridges can cause severe damage to concrete structures, leading to the need for costly repairs.

The corrosion of steel reinforcement is one of the main causes of damage to RC structures. During operation, typical in aggressive environments where moisture, salt, or acids are present, these agents penetrate through concrete pores. This can significantly reduce the strength and durability of the structure [26–28].

One of the main factors contributing to corrosion is chlorides, which are used to combat ice in winter. Numerous studies confirm that chlorides significantly accelerate the corrosion of reinforcement, typically in areas with frequent winter precipitation. These aggressive substances penetrate through microcracks in the concrete, reaching the steel reinforcement bars. As a result, the steel bars expand, causing further cracks in the concrete and its destruction [10].

Reinforcement corrosion occurs due to the penetration of chlorides found in de-icing agents or seawater. This leads to the formation of iron oxides, which increase in volume, causing the concrete to crack. Furthermore, the carbonation of concrete, resulting from the reaction of atmospheric carbon dioxide with calcium hydroxide, lowers the pH level and facilitates access of corrosive agents to the reinforcement. Chlorides significantly accelerate the reinforcement corrosion process, leading to a loss of the concrete structure's strength. It is also important to note that chloride-induced corrosion leads to the localized pitting corrosion of the reinforcement, which reduces load-bearing capacity, particularly in prestressed beam bridges. This is especially critical for bridges located in areas with high humidity and where salt and chemical agents are used for ice control. This can result in the

blistering and delamination of the concrete, which over time can pose a serious threat to structural stability [29].

Corrosion can also be caused by other chemical effects, such as sulfate attacks, where sulfates infiltrating the concrete interact with calcium in the cement material, forming expansive products that cause the concrete to crack. This can lead to damage to the internal structure of the concrete and the formation of cracks through which moisture can penetrate. Sulfate attacks are a common issue for many bridges located in areas with high water levels and significant amounts of sulfate compounds in the soil [30,31].

Environmental factors significantly contribute to the deterioration of RC structures. Adverse environmental conditions, such as temperature fluctuations, humidity levels, and air and water pollution, can accelerate the degradation of structures [32].

Bridge structures in areas with pronounced seasonal temperature variations are continuously exposed to thermal cycles of freezing and thawing, which promote the development of cracks and damage. It is essential to consider the thermal characteristics of materials and design structures to withstand these fluctuations. Such cyclic processes significantly weaken the concrete matrix and reduce adhesion with the reinforcement. For instance, during winter, moisture entering concrete pores freezes, causing cracks due to frost expansion. This is the primary cause of damage to concrete elements in cold climates. Continuous temperature fluctuations, particularly the freezing and thawing of water in concrete pores, can lead to frost damage, resulting in its deterioration. In regions with cold winters, these factors are particularly critical. Concrete's high water absorption capacity means that when water in its pores freezes, it expands, leading to cracks and material damage. Such damages are often observed in areas with significant temperature variations [33].

On bridges located in regions with prolonged winters, frost cracks caused by the cyclic freezing and thawing of water within the concrete structures are typically frequent. This damage can result in localized pore expansion or even the detachment of large concrete sections, necessitating repairs or complete replacement of damaged areas. In Canada, where freezing cycles have a pronounced effect, bridge studies have shown that cracks in concrete increased by 30% during the first 10 years of operation. To restore damaged elements, UHPC was used, which minimizes crack formation due to its high mechanical properties [34].

High humidity is also a factor contributing to the deterioration of bridge structures. Operating conditions are particularly critical for bridges in coastal areas or regions where salts are intensively used to combat icing. Salt tends to penetrate the concrete and corrode the steel elements, leading to the loss of primary structural characteristics.

Aggressive environments, such as salty or sulfate-rich groundwater and industrial emissions, pose a serious threat to RC bridges. Chemical reactions between aggressive substances and concrete components lead to the formation of microvoids, strength loss, and weakened adhesion between concrete and reinforcement. On bridges in coastal regions, corrosion caused by seawater is a primary factor in degradation, with sulfate-affected concrete areas losing up to 40% of their strength within the first 15 years of operation.

One of the most insidious mechanisms of RC bridge degradation is the gradual accumulation of micro-damage in the concrete, which initially does not affect overall strength but eventually leads to significant structural weakening. This damage is often caused by a combination of dynamic loads, temperature effects, and the natural aging of materials. Microcracks may occur even due to minor localized stress concentrations, such as in areas of stress concentration near element joints or at points of contact with supports.

Another critical factor is external air pollution. High emissions of nitrogen oxides and sulfur compounds, combined with emissions from vehicle engines, can contribute to chemical attacks on the concrete and steel elements of the bridge. This, in turn, can lead

to the destruction of the concrete shell and the weakening of the structure's strength, as accelerated degradation occurs due to chemical reactions with pollutants such as sulfur compounds or nitrogen oxides [35].

The natural aging of materials is another significant factor affecting the durability of bridge structures. Over time, concrete loses part of its rigidity due to the gradual relaxation of stresses, and reinforcement may lose its mechanical properties due to corrosion and fatigue. This phenomenon is particularly characteristic of bridges that have been in service for over 40 years.

The greatest danger to RC bridges lies in the combination of various factors that amplify each other's adverse effects. For instance, freeze–thaw cycles combined with high levels of chlorides in the environment significantly accelerate reinforcement corrosion and concrete degradation.

Vibrations caused by high-speed traffic create variable stresses in the concrete and reinforcement. This is particularly true for bridges with long spans, where vibrations can reach resonance levels, significantly weakening the structure. In bridges with high-speed railways, vibrations cause a loss of adhesion between the concrete overlay and reinforcement in compression zones. This leads to the formation and propagation of long horizontal cracks.

### *2.3. Research on the Behavior and Strengthening of Reinforced Concrete Bridge Structures*

Research into the behavior of RC bridge structures is a vital part of scientific and practical activity, as it not only ensures infrastructure reliability but also aids in developing methods to improve their lifespan and durability. The study of these structures encompasses many aspects, from damage assessment to strengthening, as well as the integration of new technologies for evaluating their condition and performance.

One of the earliest stages of studying RC structures involved examining their strength and stability under operational loads. For example, French engineer Gustave Eiffel emphasized the importance of investigating structures subjected to various mechanical loads and environmental influences. His research laid the groundwork for subsequent efforts to enhance the strength and durability of structures [36].

In the mid-20th century, many researchers from various countries began actively working on improving computational models of RC structures, particularly through the use of mathematical modeling methods such as the finite element method (FEM). This enabled more accurate assessments of the stress–strain state of structures under various loads. Significant contributions to this field were made by John Miller and James Burns, who focused on the mechanism of crack formation and its impact on structural strength. They determined that surface cracking in RC bridge structures could be one of the primary reasons for their reduced operational capacity [37,38].

The damage and destruction of RC structures of any cross-section are exacerbated by normal or inclined cracks caused by load effects. Based on the progression of cracks, scientists established calculation algorithms for determining the load-bearing capacity of bending RC elements, specifically the strength calculations for inclined and normal sections. These methods of calculation began to develop when the first studies of RC elements revealed failures occurring not only along normal cracks but also along inclined ones.

The complexity of calculations for RC structures is evidenced by the fact that numerous scientists have contributed to this field, including Dmitrenko A.O., Dorofeev V.S., Karpjuk V.M., Golishev O.B., Bambura A.M., Doroshkevych L.O., Maksymovych S.B., Maksymovych B.Yu., Klymenko Ye.V., Regan P.E., Mörsch E., Ritter W., Talbot A.N., and Leonhardt F. [39–45]. The calculation of reinforced concrete structures that considers the initial load level, stress–strain state, accumulated damage, corrosion during operation,

strengthening under prior loading, and subsequent repair remains insufficiently studied in existing research.

In his research on RC structures, Talbot characterized the behavior of RC elements after crack formation as a strut system. Further studies proposed the most rational method, adopting the so-called “truss analogy”, which likened an RC element resisting shear forces to a diagonal truss [46]. According to this theory, the upper chord corresponds to the compressed concrete zone, while the concrete web represents compressed diagonals. Simultaneously, the lower chord corresponds to the tensioned reinforcement, and the truss struts are represented by vertical transverse reinforcement, with inclined reinforcement functioning as tensioned diagonals. This method determined the load-bearing capacity of RC structures based on tensile principal stresses at the neutral axis level. Subsequent work refined this approach [47].

On the topic of retrofit, given the limited resources available from transportation companies for the interventions discussed in Section 3, new cutting-edge technologies for the structural risk assessment of existing bridges are needed to select the worst cases for retrofit. Among these, MTInSAR data [48] can be used as early warning systems based on structural displacements recorded by satellites. UAV photogrammetry and MTInSAR data can be combined to reveal the occurrence of possible subsidence phenomena leading to structural damage such as cracking in the embankment zone [49].

Due to certain limitations of the truss analogy and significant discrepancies from real-world conditions, researchers developed new methods, including the limit equilibrium method, which gained widespread use by transitioning from conventional to actual (real) RC element behavior.

Noteworthy contributions include the works of Dorofeev V.S., Bambura A.M., and Golishev O.B., which enabled predictions of the stress–strain state at any stage of an element’s loading, determining the load-bearing capacity of normal and inclined sections. Their results demonstrated high convergence, with the variation coefficient of deviations from experimental values not exceeding 10%.

Significant studies that addressed the use of real deformation diagrams for concrete and reinforcement steel, as well as refined RC structure calculation methods, include works by Pavlikov A.M., Mykytenko S.M., Bambura A.M., Babich Ye.M., Dorofeev V.S., Shkurupiy O.A., Azizov T.N., and Barashikov A.Ya. [50–53].

There are many damaged bridges in the world, and they are damaged during their operation. There is a need to strengthen and restore reinforced concrete bridges, which is a more environmentally friendly option, since the manufacture of new reinforced concrete bridges requires a significant amount of cement which significantly increases CO<sub>2</sub> emissions into the environment during the manufacturing process.

#### 2.4. Conclusions for Section 2

The primary causes of damage to RC bridges include mechanical impacts, corrosion processes, dynamic loads, and temperature fluctuations. Structural deformations result from overloading, vibrations caused by traffic movement, and seismic activity, leading to the accumulation of cracks and progressive material degradation. The corrosion of reinforcement, particularly due to chloride penetration and concrete carbonation, is a critical threat to bridge durability, causing a significant reduction in load-bearing capacity. Additionally, material fatigue and exposure to aggressive environmental conditions accelerate the deterioration of concrete structures. Therefore, systematic bridge condition monitoring, early defect detection, and the implementation of modern strengthening techniques are essential to ensure the long-term performance and safety of RC bridges.

### 3. The Use of Modern Materials for Strengthening Reinforced Concrete Bridges

#### 3.1. Determining the Actual Stressed-Deformed State in Case of Damage

A crucial area of research is determining the durability of RC structures. Studies have identified key factors that reduce structural lifespan, including mechanical loads, thermal fluctuations, and aggressive chemicals in the environment.

Thus, scientific studies conducted worldwide have significantly expanded our understanding of RC structure behavior, damage mechanisms, and reinforcement methods. Investigating various damage mechanisms, such as corrosion and material fatigue, along with the effects of new materials for reinforcement, has facilitated the development of effective methods to preserve and extend the lifespan of such structures. These studies form the basis for new technologies in construction and infrastructure, ensuring the reliability and durability of critical infrastructure, such as bridges and other RC structures [38].

Determining how various damage types affect RC structure performance is increasingly relevant and necessary in Ukraine, aiming to assess the actual technical condition of structures and bridges. Damage influences structural behavior in complex ways, making existing methods only a partial solution for determining the stress–strain state of such constructions.

Inclined bending, caused by damage and defects in bent RC elements, was noted in [54]. Due to defects and production-related damage, the inclination angle of the force plane changes, altering the strength and deformation characteristics of the element. The study of T-shaped RC beams with flange damage or compression zone losses was addressed in [55].

Non-destructive methods for diagnosing and monitoring RC structures are receiving growing attention. Techniques such as digital image correlation (DIC) (Figure 3) and sensor monitoring systems allow for the early detection of damage without requiring major repairs. This is particularly crucial for bridges and other critical structures, where reduced diagnosis and repair time significantly lowers costs and ensures structural safety.



**Figure 3.** An example of using digital image correlation for determining strains and deflections of reinforced concrete structures (authors' own research).

In conclusion, it can be stated that determining and establishing the actual stress–strain state at different stages of loading during the operation of RC bridge structures under damaged conditions and assessing their residual load-bearing capacity is a highly relevant issue today and requires the detailed examination and refinement of calculation methods. Damage should be considered in various forms, such as concrete spalling, damage to the concrete compression zone, the reduction in cross-sections in working reinforcement due

to corrosion, and the consideration of the loss of cross-section in thermally strengthened reinforcement layers.

### 3.2. Reinforcement Using Various Methods with the Help of Composite Materials

In recent decades, considerable attention has been given to studying the effects of new materials on RC structure behavior and methods of strengthening them (Figures 4 and 5). The use of composite materials such as carbon fibers has significantly enhanced the efficiency of RC structure reinforcement. These composites exhibit high corrosion resistance and can be utilized to strengthen structures in aggressive environments.



**Figure 4.** An example of the strengthening of reinforced concrete structures by carbon fiber-reinforced polymers (authors' own research).

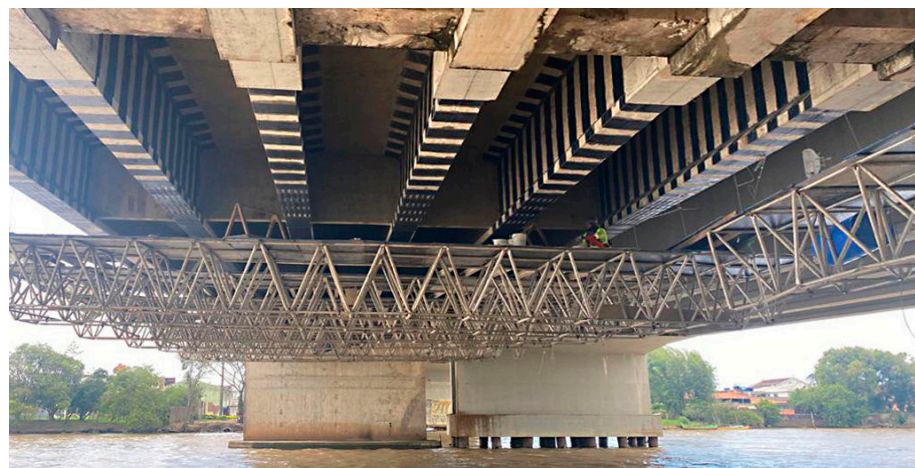


**Figure 5.** An example of strengthening of the reinforced concrete bridge in Brazil with composite materials [56].

The use of composite materials, particularly fiber-reinforced polymers (FRP), for strengthening reinforced concrete (RC) bridges has significantly increased over the past two decades (Figure 6). This growth is driven by the advantages of composites, including high strength-to-weight ratio, corrosion resistance, and ease of application compared to traditional strengthening methods [57,58]. Despite the lack of centralized global data, various studies and reports indicate a steady rise in the adoption of FRP for bridge rehabilitation worldwide [59]. The estimated trend suggests an exponential increase in the number of RC bridges strengthened with composites due to advancements in materials, growing

infrastructure needs, and regulatory acceptance [60]. The following graph approximates the global usage of composite materials for strengthening RC bridges over the last 20 years based on available research and industry trends.

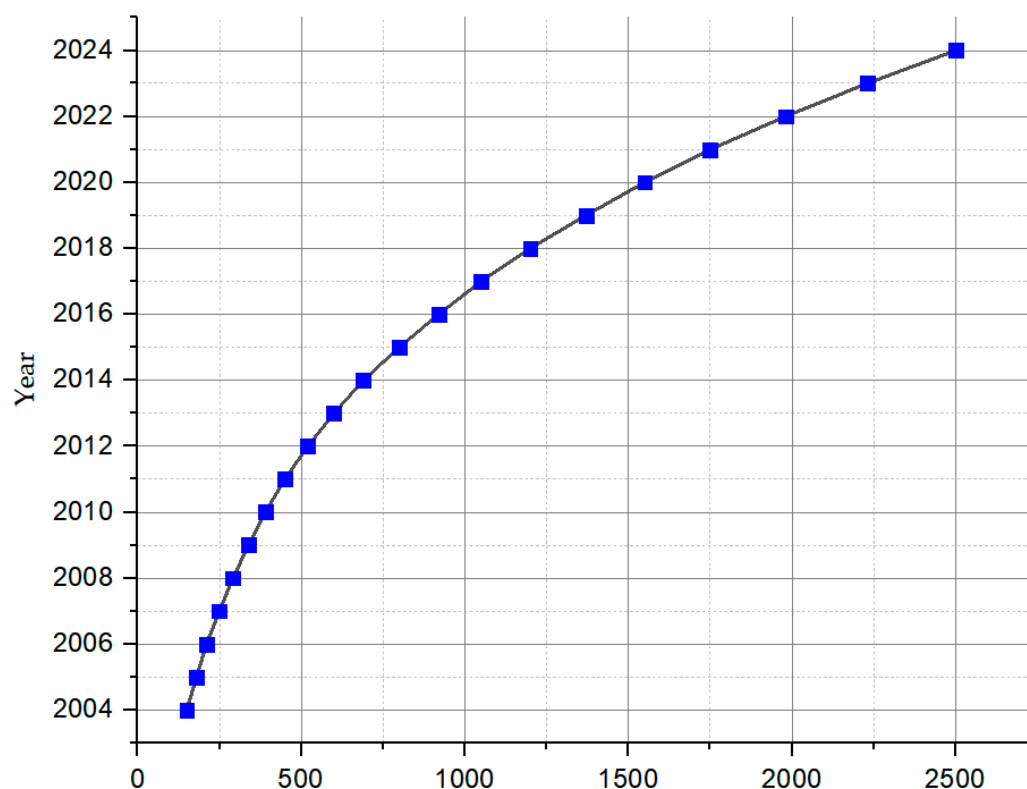


Figure 6. Estimated global use of composite materials for RC bridge strengthening (2004–2024).

The strengthening of the RC structures is a crucial stage in ensuring their durability and safety, particularly in the context of material aging, load impacts, and aggressive environments [61,62]. There are many methods for strengthening RC structures, which can be broadly categorized into traditional and modern methods, utilizing advanced materials such as composites. These methods differ in effectiveness, cost, time required for implementation, and the longevity of the results [37].

Traditional strengthening methods for RC structures include options such as adding steel elements or reinforcement, increasing the thickness of the concrete layer, using additional steel frames or girders, and attaching external steel plates or braces [55,56]. These methods have been widely used in older construction practices and have proven effective in correcting structural deficiencies, particularly for increasing strength in bending, shear, and compression. These methods are based on mechanically anchoring additional elements (concrete or metal) to the existing structure, significantly enhancing its load-bearing capacity. Such cross-sectional enlargements are common strengthening methods, as highlighted in the works of Barashikov A.Ya. [63] and Kryvosheev P.I. [64].

However, these methods also have disadvantages, the main ones being the added weight of the materials, which can overload the existing structure, as well as the need for substantial labor, increasing the cost of work. Furthermore, traditional strengthening methods can deteriorate the esthetic qualities of the structure and create difficulties when working in constrained spaces, particularly when strengthening actively used bridge structures. Increasing the concrete section adds considerable weight to the structure, which negatively affects the load-bearing capacity of lower-lying components, also requiring additional engineering approaches to access damaged areas, such as the concrete compression zone [65].

Research into strengthening damaged RC structures with external steel reinforcement has been conducted in several scientific works, including those by Robers T.M. [66] and Irwin C.F. [67]. Notably, a study was conducted on strengthening existing concrete bridges during operation by bonding steel reinforcement plates to RC structures using epoxy resin.

Modern strengthening technologies include the use of composite materials, fiber-reinforced concrete, high-quality concrete mixes, and injection methods, all of which effectively strengthen structures without the need for complete reconstruction. Each of these methods has specific advantages and can be used depending on the type of damage, loading conditions, and operating environment [68].

One of the most effective and commonly used methods is reinforcement using carbon materials. Carbon tapes and sheets are extremely strong and lightweight materials that have high resistance to corrosion, ultraviolet radiation, and chemical impacts [69]. They are actively used to strengthen reinforced concrete structures, particularly in areas subjected to the highest loads, such as beams and bridge columns. The reinforcement process is carried out by bonding carbon tapes or sheets to the concrete surface, which helps to distribute the load evenly and reduces the risk of cracking. Composite materials for strengthening RC beams are divided into CFRP (carbon fiber-reinforced polymer) and FRCM (fiber-reinforced cement matrix) (Figures 7 and 8) depending on the installation method [70]. The high effectiveness of such reinforcements is discussed in works [71–73].

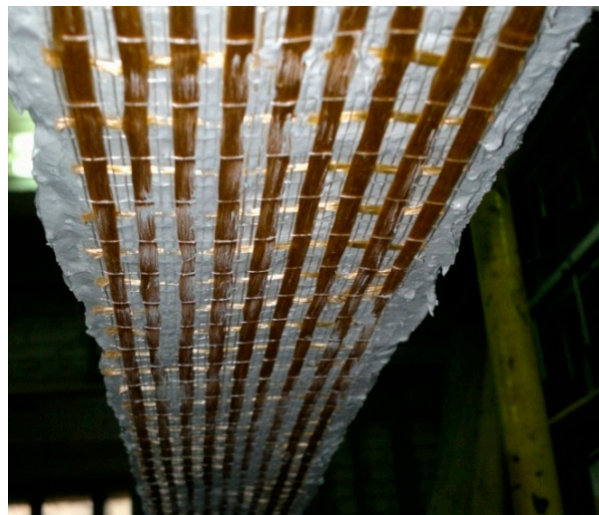


**Figure 7.** An example of the strengthening of reinforced concrete structures by fiber-reinforced cement matrix (authors' own research).

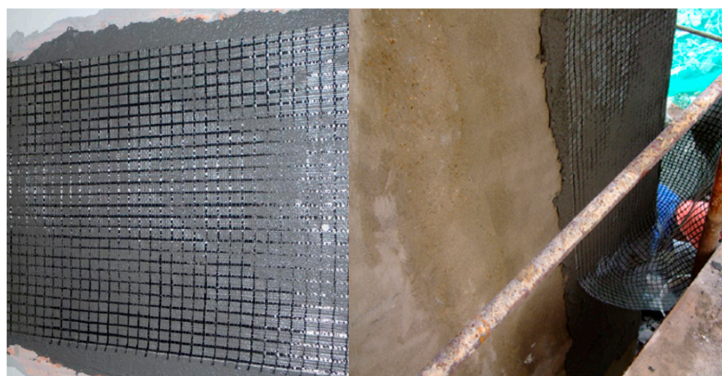


**Figure 8.** Application of FRCM on real RC structures [74].

Modern carbon composite manufacturing technologies allow for materials with a low coefficient of thermal expansion, making them ideal for use in conditions of temperature

fluctuations, such as winter periods in cold climates. One of the key advantages of carbon materials is their high tensile strength, ensuring long-term reinforcement without significantly increasing the weight of the structures, which is particularly important for bridge structures [68].

Another effective method is the use of fiber-reinforced concrete for strengthening RC structures. Fiber-reinforced concrete is a type of concrete that incorporates microfibers made of metal, plastic, or other fibrous materials, which enhance its crack resistance and reduce the likelihood of microcracks. Due to its properties, fiber-reinforced concrete is widely used for strengthening existing bridge structures as well as manufacturing new elements such as slabs and columns [75]. Its high compressive strength and improved plasticity allow for the effective redistribution of loads during bridge operation, reducing the risk of deformation and cracking [76].

The use of high-quality concrete is another critical stage in strengthening RC structures. High-strength concrete can be used both to reinforce existing structures and to create new elements that must withstand significant loads. This material is particularly useful for strengthening structures subjected to mechanical or dynamic loads. High-strength concrete, typically based on microsilicates or other additives, provides additional strength and wear resistance, making it ideal for use in bridge structures [77,78].

In the case of concrete damage due to reinforcement corrosion or material aging, an injection strengthening method is employed. The injection of special polymer materials, such as epoxy resins or silicone compounds, into cracks and pores in the concrete not only strengthens the structure but also prevents further damage development. The injection of these materials allows for the complete restoration of the strength of damaged areas, as well as improving the water resistance of the structures, which is especially important for bridges exposed to rain, snow, and road chemicals [79,80].

The injection method has a significant advantage in that it allows for work to be carried out without significant disruption to the normal operation of the structure. This is particularly important for bridges, where complete reconstruction could lead to long delays and substantial costs. Injection allows for work to be carried out on limited areas of the structure without the need for dismantling or altering its geometry [81,82].

One of the most promising approaches is the use of combined reinforcement methods. For instance, combining carbon materials with fiber-reinforced concrete or high-quality concrete mixtures can yield even more effective results. This approach significantly enhances the strength of the structures and ensures their stability during operation under high loads or in aggressive environments [83].

All these methods can be used either individually or in combination, offering a wide range of options for selecting the optimal approach depending on the specific conditions. The choice of reinforcement method depends on many factors, such as the type of damage, the age of the structure, the loading conditions, and the operating environment. However, modern reinforcement approaches for RC structures allow for significant improvements in their operational characteristics and extend the service life of bridge structures.

Additionally, modern reinforcement methods actively use high-strength composite materials that can be integrated into the structure of bridge constructions. For example, the use of nanomaterials, such as nanoparticles in concrete or additives that enhance strength and wear resistance, is a promising direction for strengthening structures [84,85]. These materials are capable of not only increasing mechanical properties but also improving the durability of structures in aggressive environments. However, additional research is needed to assess their compatibility with traditional materials and operational properties for use in concrete structures.

An important aspect is also the technology of non-destructive reinforcement of structures. These methods involve strengthening without significant changes to the geometry of the structure, which is crucial for bridges where each stage of reconstruction or repair is associated with high costs and risks. One such method involves the use of fiber-optic sensors to monitor the condition of structures in real-time. This allows for the timely detection of damage and deformations without the need for physical intervention in the structure, which is important for improving safety and reducing maintenance costs [86].

Despite the high effectiveness of the latest technologies, traditional reinforcement methods remain popular and effective. Specifically, methods involving the use of steel plates and welding continue to be applied for strengthening certain types of bridge structures, particularly in areas where access to modern materials is limited or costly. These methods are relatively low-cost and can be used for simple repairs that do not require significant changes to the bridge's structural elements. However, in cases of serious damage, they often cannot provide sufficient effectiveness compared to modern composite materials.

One of the greatest achievements in bridge strengthening is the combination of traditional and modern methods. For example, welding steel plates can be used as temporary reinforcement, after which composite materials are applied for final strengthening. This combined approach allows for effective repair and modernization of structures, reducing costs and time required for the work.

No less important is the reinforcement of bridge structures in response to changing environmental conditions and impacts. Considering that most bridges are used for decades, they are exposed to aggressive environmental factors such as road salts, increased humidity, or high temperatures. Traditional materials are not always capable of providing adequate protection against corrosion and other external factors. In such cases, the use of modern reinforcement methods, particularly carbon and fiber composites, becomes necessary to extend the service life and maintain the strength of the structures.

Overall, combined approaches that integrate traditional and modern reinforcement methods are the most promising in the field of bridge repair and reconstruction. They enable significant reductions in costs and work time, while ensuring high durability and safety. The development of technologies and materials continues to improve reinforcement processes, which, in turn, has a significant impact on enhancing the efficiency and reliability of reinforced concrete bridges.

Thus, strengthening reinforced concrete bridge structures is an important stage in their operation, allowing for the long-lasting and safe service of structures regardless of loading conditions and environment. The successful application of both traditional and cutting-edge reinforcement technologies significantly improves the technical characteristics of structures and enhances their resistance to various impacts.

The strengthening of the reinforced concrete bridges using composite carbon materials is a much more environmentally friendly option, since the steel that are traditionally used for reinforcement requires a large amount of electricity during production and cause significant CO<sub>2</sub> emissions. Moreover, composite materials based on carbon fibers are not associated with the use of large amounts of energy sources, which is better for the environment and significantly reduces CO<sub>2</sub> emissions during the manufacturing process.

### 3.3. Conclusion for Section 3

Modern strengthening methods for RC bridges focus on enhancing durability, reducing structural weight, and improving resistance to corrosion. The use of composite materials such as carbon and basalt fibers provides effective reinforcement while minimizing additional loads. Furthermore, fiber-reinforced concrete, high-performance concrete mixtures, and injection-based repair techniques help to restore localized damage and improve overall

structural capacity. The integration of both traditional and advanced strengthening technologies significantly extends the service life of bridge structures, reduces maintenance costs, and enhances structural reliability.

## 4. Innovative Approaches to the Ecological Restoration of RC Bridges

### 4.1. Environmental Challenges of Demolishing Reinforced Concrete Bridges

Reinforced concrete bridge structures are key elements of transportation infrastructure, but their operation over time leads to wear, damage, and a reduction in load-bearing capacity. The decision between restoring damaged structures and demolishing them for subsequent new construction is not only an engineering but also an environmental issue [87,88]. The restoration of structures is often considered a more environmentally justified approach; however, to substantiate this claim, it is important to consider key aspects, including environmental impact, energy consumption, waste generation, and carbon dioxide emissions [89].

The demolition process of reinforced concrete bridges generates a large amount of construction waste, which often includes concrete debris, reinforcement, and other materials. The improper disposal of concrete residues can lead to soil and water pollution due to the release of chemicals used in construction materials. The disposal of old concrete in landfills also creates long-term environmental risks. These types of waste are difficult to recycle due to their mixed composition and the presence of impurities such as paints, mastics, or chemical residues [90,91]. According to global research data, on average, only 30–40% of materials from demolished structures are recycled, while the rest is sent to landfills.

In addition, the disposal of construction materials is associated with high energy costs. Concrete recycling requires crushing, sorting, and reinforcement separation, which significantly increases the carbon footprint. For example, crushing 1 ton of concrete debris requires approximately 200 kWh of electricity, and the transportation of residues to disposal sites generates additional greenhouse gas emissions [92]. Concrete debris left in landfills may release harmful substances such as heavy metals or chloride residues, which eventually penetrate the environment. Reinforcement in concrete that has suffered corrosion damage is often unsuitable for reuse, increasing metal waste. Equipment for crushing concrete and separating reinforcement consumes large amounts of energy, further increasing the overall carbon footprint of the process [93].

### 4.2. Sustainable Restoration Strategies for Reinforced Concrete Bridges

The process of restoring reinforced concrete bridges offers several environmental advantages compared to demolition and the complete replacement of structures. One of the key benefits is the significant reduction in the volume of construction waste. For example, restoring a damaged compressed concrete zone using modern repair mortars avoids the need to dismantle large sections of the structure. The use of high-strength repair mortar Sika MonoTop-4012, reinforced with fibers and containing recycled raw materials that reduce the carbon footprint, helps to minimize the environmental impact [94,95].

Another important aspect is the reduction in CO<sub>2</sub> emissions. Cement production, a major component of concrete, accounts for up to 8% of global carbon dioxide emissions. During the restoration of structures, the demand for new concrete is minimal, as the main part of the structure is preserved. According to calculations, restoration can reduce CO<sub>2</sub> emissions by 50–70% compared to the complete replacement of structures [96].

Moreover, the use of modern materials such as FRP (fiber-reinforced polymers) or UHPC increases the durability of structures, reducing the need for repeated repairs and additional material costs. For instance, FRP composites provide resistance to corrosion and mechanical damage, and their installation requires minimal energy consumption [71–73,97].

The construction of new bridges is a significantly energy-intensive process, involving material extraction, processing, transportation, and assembly [98]. Estimates indicate that building a medium-sized bridge requires up to 10,000 GJ of energy, whereas restoring a severely damaged bridge requires approximately 30–40% of this energy to restore load-bearing capacity to operational levels. Reducing energy consumption on such a scale makes restoration an economically and environmentally attractive solution [98]. Additionally, modern technologies allow for the automation of some repair works, reducing the need for large quantities of heavy machinery that consumes fuel. For example, the use of robotic systems for applying repair compounds significantly shortens the time and energy costs of restoration [37].

Although the restoration of RC bridges offers significant environmental benefits, it is not entirely free from environmental impact. The production of composite materials, UHPC, or repair mortars also results in CO<sub>2</sub> emissions and energy consumption. However, in most cases, this impact is significantly lower compared to the construction of new bridges. Retaining existing structures also entails risks related to the insufficient durability of restored areas. In cases where repairs are performed with technological violations or without using high-quality materials, the need for repeated restoration may nullify all environmental advantages.

Nevertheless, a comprehensive approach to improving RC bridge restoration technologies must be implemented, including the development of innovative materials, the refinement of calculation methodologies, and the application of modern monitoring tools [85,86]. Systematic research should focus on enhancing the accuracy of structural condition assessments, predicting their durability, and determining the most environmentally friendly and effective restoration methods. Additionally, it is essential to consider the life cycle of materials used in repairs and select those with minimal environmental impact. For instance, introducing long-lasting composite materials with a low carbon footprint can significantly reduce environmental costs. Only by integrating advanced technologies and eco-friendly practices can restoration work maximize environmental benefits and extend the service life of bridges without harming the environment. Modern technologies for monitoring and controlling the technical condition of RC bridges play a key role in ensuring their durability and minimizing negative environmental impact. The use of innovative devices, such as the digital image correlation (DIC) system, allows for the highly accurate tracking of even minor damage in concrete structures. This enables timely responses to the emergence of microcracks or localized deformations, preventing their further development [99–102].

DIC provides a non-contact, high-precision real-time analysis of structural conditions, representing a significant breakthrough compared to traditional methods. Detecting minimal deformations at early stages helps to avoid major damage that would require significant material and energy expenditures for restoration. For example, when reinforcement corrosion or concrete carbonation is detected at the initial stages, repair work can be limited to crack injection or the localized application of protective coatings, minimizing the generation of construction waste.

Such monitoring accuracy enables the more efficient planning of repair activities, reducing the consumption of materials, energy, and resources. Decreasing the volume of major repairs positively impacts the environment by reducing the need for extracting and transporting new materials, as well as minimizing CO<sub>2</sub> emissions associated with these processes. Additionally, structural condition monitoring using DIC reduces the risk of sudden bridge collapses, which can result in catastrophic environmental consequences, including water pollution, ecosystem damage, and the generation of large amounts of waste. Regular monitoring helps maintain the stability of structures over time, significantly extending their service life [103].

The introduction of such technologies in the field of RC bridge monitoring not only enhances their safety level but also provides substantial environmental advantages. Digital structural condition control is not just an engineering solution but also an important tool for sustainable development, allowing for the harmonious combination of technological progress with environmental care.

#### *4.3. Conclusions for Section 4*

The restoration of bridge structures presents a viable alternative to demolition and new construction, significantly reducing construction waste and CO<sub>2</sub> emissions. The use of modern materials, such as ultra-high-performance concrete (UHPC) and fiber-reinforced polymers (FRP), enhances structural longevity while minimizing environmental impact. The application of digital monitoring technologies, including the digital image correlation (DIC) method, enables the early detection of structural damage, allowing for timely and localized repairs. The combination of advanced materials and diagnostic techniques reduces energy consumption, improves infrastructure sustainability, and supports the long-term resilience of RC bridges. Ecological restoration, therefore, serves as an effective solution within the framework of sustainable development.

### **5. Conclusions**

Research on the damage, calculations, and reinforcement of reinforced concrete bridge structures allows for several key conclusions regarding the current state, main challenges, and prospects for the development of this field.

Reinforced concrete bridges, being critical elements of transport infrastructure, are subject to significant operational loads, environmental impacts, and natural phenomena. The main causes of damage include mechanical effects, particularly material fatigue from repeated cyclic loading, the overloading of structures, impacts from vehicles, and seismic actions. The corrosion of reinforcement caused by the penetration of moisture, salts, and chemically active substances is a critical issue, particularly for bridges located in aggressive environments. Thermal fluctuations, including extreme temperatures, affect the stress–strain state of structures and contribute to crack formation.

In the calculation of reinforced concrete bridge structures, an important aspect is considering material degradation over time, crack formation, and their impact on the bearing capacity of the structure. Modern approaches to modeling, such as numerical methods like finite element analysis, allow for the consideration of complex physical–mechanical processes in materials. Studies confirm that models accounting for real operating conditions, particularly long-term dynamic impacts, provide a more accurate prediction of the durability of structures. However, the need for standardized methodologies and advanced software remains relevant.

Regarding the strengthening of RC structures, traditional methods such as adding steel elements or overlays remain popular due to their reliability. However, modern approaches, particularly the use of composite materials such as carbon strips, sheets, and other polymers, show significant advantages in improving durability and reducing the weight of structures. Innovative materials offer higher corrosion resistance and help to avoid significant increases in the weight of the structure, which is particularly important for bridges with high traffic capacity. A comparison of different reinforcement methods shows that the choice of a specific solution depends on the nature of the damage, operating conditions, and project budget. Based on the conducted analysis, it can be stated that the development of technologies for diagnostics, calculations, and strengthening of the RC bridges is critical for ensuring their longevity and safety. Further research should focus on

studying the long-term effects of aggressive environments on reinforced concrete, as well as optimizing construction materials for reinforcement.

Special attention is required for the integration of digital technologies, such as the digital image correlation (DIC) method, for the precise analysis of deformations and damage. The use of such approaches, in conjunction with innovative materials, will enable the creation of more effective strategies for the maintenance, repair, and modernization of bridges, ensuring their durability under modern transportation loads.

The restoration of RC bridges is an effective way to minimize environmental impact, especially in today's world, where sustainable development is becoming increasingly important. Restoration helps to preserve valuable resources, reduce construction waste, and lower the carbon footprint of infrastructure projects. However, to achieve maximum environmental efficiency, it is essential to adhere to technological requirements, use advanced materials, and conduct regular structural condition monitoring. RC bridge restoration is both a technical solution and an ethical response to climate change and environmental risks.

The implementation of modern monitoring technologies, such as digital image correlation (DIC), ensures the early detection of damage in RC bridges, enabling prompt localized repairs. This not only extends the service life of structures but also significantly reduces environmental impact by minimizing construction waste, reducing the demand for new materials, and lowering CO<sub>2</sub> emissions. Thus, monitoring technologies contribute not only to infrastructure safety but also to sustainable development by harmonizing technical solutions with environmental goals.

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