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**III International Scientific and Practical Conference
«Global scientific dialogue: challenges, innovations,
and future horizons»**

**September 22–25, 2026
Hamburg, Germany**

ISBN - 979-8-90553-916-9

DOI – 10.46299/ISG.2026.2.3

GLOBAL SCIENTIFIC DIALOGUE: CHALLENGES, INNOVATIONS, AND FUTURE HORIZONS

Proceedings of the III International Scientific and Practical Conference

Hamburg, Germany
September 22–25, 2026

UDC 01.1

The III International scientific and practical conference “Global scientific dialogue: challenges, innovations, and future horizons” (September 22–25, 2026) Hamburg, Germany. International Science Group. 2026. 172 p.

ISBN – 979-8-90553-916-9

DOI – 10.46299/ISG.2026.2.3

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MODERN MATERIALS AND INNOVATIVE TECHNOLOGIES IN BRIDGE CONSTRUCTION

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The global bridge construction market is undergoing a dynamic transformation driven by aging infrastructure, climate change, and increasing urbanization. In 2024, the global bridge construction market was valued at \$368.55 billion [1]; in 2025, it was valued at \$724.7 billion [2]; and it is projected to reach \$1.0 trillion by 2032 [2].

Building bridges helps improve traffic flow and economic integration.

Demand for new engineering structures in North America is driven by rapid urbanization, infrastructure expansion, the growth of e-commerce, and, consequently, increased transportation volumes, and is stimulated by government investment, whereas in Europe, demand is driven by the expansion of connectivity projects and the development of transportation systems; The focus is on the repair and modernization of outdated crossings using EU funds and within the framework of sustainable development policy [1].

The growth of logistics and freight transportation is creating a demand for strong and durable bridges; climate change and the high frequency of natural disasters are increasing the demand for sustainable bridge construction. The issue of bridge durability has become a critical concern today.

To address these challenges, the civil engineering industry is moving away from traditional, monolithic reinforced concrete structures in favor of advanced composites, self-healing systems, and digital life-cycle management of structures.

The purpose of our study is to review, summarize, systematize, and critically analyze modern material and innovative technologies, and to assess their potential for use in bridge construction.

Concrete remains the traditional material in the bridge construction market. The dominance of this material is explained by its versatility, durability, and relative cost-effectiveness. Its resistance to weathering, corrosion, and fire broadens its application and makes it suitable for diverse regions, while the availability of raw materials for concrete bridges ensures the cost efficiency of its use in construction [1]. Owing to its high compressive strength, reinforced concrete remains the primary structural material of modern bridge engineering. However, it still has an inherent propensity for cracking under the influence of tensile stresses and temperature fluctuations. In an aggressive

bridge environment, the emergence of cracks opens pathways for the ingress of water, oxygen, and chlorides, which triggers accelerated corrosion of the steel reinforcement.

In order to extend the service life of buildings, more and more countries are adopting new materials and technologies.

The fastest-growing segment of the bridge construction market is the use of stainless steel composites, thanks to their high strength and faster installation. The high tensile strength of steel-composite bridges extends their service life, which is particularly important for regions prone to natural disasters. In addition, the advantages of steel composites for bridge construction include advances in corrosion-resistant coatings, weather-resistant steels, and galvanizing methods [1].

But today, these durable materials are considered “traditional,” while newer, innovative materials and technologies are expanding existing possibilities. The chemical and materials industries are rapidly evolving and introducing innovations by integrating digital and smart features into materials, thereby improving critical properties such as heat resistance, tensile strength, and corrosion resistance [3].

New materials are stronger and more environmentally friendly, and they do things that weren't possible before.

Let's examine and compare traditional materials and selected next-generation technologies (Table 1).

Table 1.

A Comparison of Traditional Materials and Selected Next-Generation Technologies

Material properties	Traditional materials	Modern Materials and Technologies	Key Differences and Engineering Advantages
Concrete Formwork	Standard structural concrete (C30/37–C50/60), w/c = 0.40–0.50	UHPC / UHPFRC with nanosilica (w/b < 0.25, fibers 1.5–3.5% by volume)	Compressive strength >150 MPa vs. 30–50 MPa; virtually zero porosity; ductility and strain hardening instead of brittle fracture.
Reaction to Scratches	Passive (no repair or autogenous healing of microcracks up to 30–50 µm only)	Active SMA alloys (NiTiNb) + crystalline additives (CA)	Active crack closure: 84–90% reduction in crack width; up to 35% recovery of stiffness; self-stressing capability (+39% load-bearing capacity).
Severe damage	Manual Injections of Epoxy Resins / PCC Mortar	Encapsulation and bacterial biomineralization (MICP)	Autonomous sealing of defects ranging from 100 to 500 µm without the need for inspection or taking the bridge out of service.

Continuation of Table 1.

Material properties	Traditional materials	Modern Materials and Technologies	Key Differences and Engineering Advantages
Structural Reinforcement	Standard carbon steel, susceptible to corrosion	Allium rebar (carbon steel, stainless steel-clad)	3 times higher fatigue and corrosion resistance; a stainless steel corrosion barrier that preserves the load-bearing capacity and manufacturability of the carbon steel core (lifespan: 100 years).
Chemical additives	Petrochemical superplasticizers, high VOC emissions.	Bioplasticizers and bio-additives (e.g., Thermax)	A 45% reduction in the carbon footprint of additives; an 80% decrease in VOC emissions.
Bridge deck waterproofing	Heat-weldable roofing membranes, bituminous membranes made from crude oil	Eco-friendly membranes (e.g., SikaProof Eco-Line)	More than 70% of the raw material base comes from renewable sources, while maintaining complete leak-tightness.
Construction method	Traditional formwork and monolithic in-situ concrete pouring	3D Printing (Robotic Extrusion)	Elimination of formwork, optimization (material placed where stresses occur), production of components in a shorter time.

Source of the table: compiled by the author based on analysis [3-14]

The following innovative material and structural technologies can be identified in modern bridge construction:

1. Next-Generation Concretes: UHPC and Nanotechnology. Ultra-high-performance concrete (UHPC) is a significant innovation in terms of the durability of engineering structures [4, 5].

□ *Mechanical and physical properties*: Ultra-high-strength concrete achieves a compressive strength of over 150 MPa, and thanks to its low water-to-cement ratio ($w/b < 0.25$) and optimized density, its porosity and permeability to chloride ions are negligible [5].

□ *Dispersed reinforcement (UHPFRC)*: Adding 1.5–3.5% high-strength steel fibers prevents brittle failure. These fibers effectively bridge microcracks, which promotes stress redistribution and achieves the strain-hardening effect. This increases the element's ductility and toughness, making it possible to design lighter and thinner slabs for bridge structures [4, 5].

□ *Nanostructural modifications*: The use of nanosilica activates pozzolanic reactions with calcium hydroxide ($\text{Ca}(\text{OH})_2$), forming a dense C-S-H phase. This eliminates weak points in the matrix and densifies the interface transition zone (ITZ) between the cement paste and the aggregate [5].

The integration of carbon nanotubes (CNTs) differs fundamentally from preceding methods. The nanotubes function as nano-reinforcement: due to their exceptional

molecular-level strength, they effectively bridge microdefects within the hardened cement paste matrix, preventing microcracks from propagating into major destructive fractures. Furthermore, CNTs exhibit high electrical conductivity. When uniformly dispersed throughout the concrete, they establish a continuous piezoresistive network within the structure. As the bridge deforms under traffic loads or experiences internal stress, the electrical resistance of the concrete shifts accordingly. This provides a distinct self-sensing capability: the structural bridge concrete itself transforms into an extensive, highly sensitive sensor capable of instantaneously signaling computerized systems regarding the onset of critical internal strain long before any cracking becomes visually detectable [6, 7].

2. Active and passive self-healing systems. The phenomenon of cracking in concrete under bridge service conditions is widespread; however, advanced materials science mechanisms enable autonomous mitigation of this phenomenon [4, 5].

Shape memory alloys (SMAs): A novel solution involves the application of pre-deformed nickel-titanium-niobium (NiTiNb) alloy rods [4, 8, 9]. SMA rebars possess the unique capability to deform and subsequently recover their initial shape upon thermal activation. Consequently, thermal activation (via electrical resistance or induction heating) following crack initiation forces the alloy to revert to its original geometry. This mechanism generates recovery forces that close the crack lips, reducing crack width by 90% in fiber-reinforced concrete (FRC) and by 84% in ultra-high-performance concrete (UHPC), while simultaneously restoring up to 35% of the original secant stiffness. On the other hand, activating the rods prior to the application of external loads enables anchorless prestressing, thereby increasing the load-bearing capacity of UHPC members by up to 39% [4]. A significant technical challenge during the induction heating of UHPC is the risk of explosive concrete spalling, induced by the dense matrix microstructure and the inclusion of steel fibers; this hazard can be effectively mitigated through the addition of low-melting-point polypropylene microfibers [4].

□ *Autogenous self-healing and crystalline admixtures (CA):* When moisture penetrates through cracks in UHPC concrete, the unhydrated cement grains resume the hydration reaction, while dissolved CO₂ causes the precipitation of calcium carbonate (CaCO₃) [5]. This process heals cracks up to 100 μm wide, and specialized crystalline admixtures significantly reduce the reaction time [5].

□ *Encapsulation and biomineralization (MICP):* For defects 100–500 μm wide, autonomous methods are used: polymer or mineral microcapsules, which rupture as the crack propagates and release repair resins, or bacterial biomineralization (*Bacillus subtilis*), in which bacteria synthesize calcium carbonate in the presence of moisture and urea [5].

Capsule-Based Concrete relies on the fact that the capsule shells added to the concrete matrix remain intact during concrete mixing but break down under mechanical stress when a crack forms.

Bio-concrete technology is based on the incorporation of spore-forming bacteria into the concrete mix along with a nutrient medium, in which they remain dormant. When a crack measuring 0.3 to 0.8 mm in width occurs in the concrete and allows

moisture and oxygen to ingress, the bacteria are activated and metabolically decompose calcium lactate. A byproduct of this chemical reaction is the precipitation of calcium carbonate (limestone), which physically fills and seals the crack within 2 to 4 weeks. Bio-concrete is a leading innovation in green construction, as it significantly reduces chloride permeability in concrete, extends the service life of structures, and minimizes repair requirements [10].

3. Sustainable chemistry and corrosion control engineering. The requirements of decarbonization and multi-criteria green building certifications (LEED, BREEAM) dictate the need to reduce the embodied carbon footprint and phase out petrochemical feedstocks [1].

□ *Bioplasticizers and environmentally friendly admixtures:* Petroleum-based additives are giving way to formulations based on plant-derived resins and biodegradable polymers. Through the application of bio-admixtures, the carbon footprint of construction chemical processes is reduced by nearly 45%, while environmental agency data indicate that volatile organic compound (VOC) emissions decrease by 80% [1].

Driven by stringent environmental regulations and the requirements of sustainable green construction, the field of construction chemicals is undergoing a fundamental shift: transitioning from conventional petrochemical-based additives toward bio-based alternatives, including plant resins, enzymes, and biodegradable polymers. Such bioplasticizers, non-toxic retarders, and bio-based waterproofing agents are currently being integrated into construction engineering practices [11].

□ *Renewable materials in waterproofing:* In modern bridge engineering, during both the construction and rehabilitation of infrastructure facilities, eco-friendly renewable waterproofing materials—particularly polymer membranes manufactured with renewable raw materials—are increasingly gaining traction. Such materials are employed for the waterproofing and protection of concrete bridge structures and bridge deck slabs, concurrently enhancing their durability and reducing the environmental impact of construction works [12]. A notable example is the SikaProof Eco-Line waterproofing membrane series, which incorporates over 70% renewable raw materials in its composition [13].

□ *Clad rebar:* Clad rebar represents a promising hybrid reinforcement technology for bridge structures. In particular, Allium Engineering has developed rebar featuring a carbon steel core encased in an outer layer of stainless steel, significantly enhancing its corrosion resistance. The technology is tailored for application in concrete bridge structures and possesses the potential to extend their service life to 100 years or more. A critical advantage of this material is its full compatibility with standard rebar fabrication and installation practices [14].

4. Industrial prefabrication, 3D printing, and digitalization. The automation of construction processes directly leads to reduced construction schedules and minimizes traffic disruptions [2].

□ *3D printing via Additive Manufacturing:* The elimination of formwork enables topological optimization. Early implementations of pedestrian bridges (notably by the

consortium of Simpliforge Creations and IIT Hyderabad) demonstrate that robotic concrete extrusion technologies allow for the fabrication of a superstructure in under two hours, facilitating immediate on-site assembly [1, 2].

□ *Mathematical modeling and digitalization*: Advanced analysis and simulation of load dynamics optimize decision-making and integration with BIM environments during the early stages of engineering design and training [2].

□ *Life-cycle optimization (LCC/LCA)*: The application of ultra-high-performance concrete (UHPC) cementitious composites and self-healing systems reduces total life-cycle costs (LCC) by 20–35% over a 50-year perspective. Furthermore, mitigating the required frequency of maintenance and repair operations decreases the embodied carbon footprint by 25–35% [5].

The implementation of novel materials and advanced technologies provides substantial advantages, notably financial cost savings, the extension of structural service life, and the mitigation of adverse environmental impacts. A comparative analysis of the benefits associated with selected technologies is presented in Table 2.

Table 2.

Engineering, economic, and environmental benefits of implementing the selected technologies

Type of Advantage	Parameter	Traditional solutions	Implementation of New Technologies	Tangible operational and engineering benefits
Durability and service life	Design service life of the structure	Standard: approx. 50 years (frequently requiring the first major rehabilitation after 15–20 years)	Allium stainless-clad rebar + concrete UHPC	Extension of failure-free service life to 100 years; 3-fold higher fatigue and corrosion resistance of bridge deck slabs.
Load-bearing capacity and dead load	Member load-bearing capacity and cross-section optimization	Thick, massive reinforced concrete slabs; load-bearing capacity governed by self-weight	UHPFRC + active prestressing with SMA (NiTiNb) alloys	A 39% increase in load-bearing capacity without the use of external anchors; enabling the design of lighter superstructures (strain-hardening). [4, 5, 8, 9].
Life-cycle operational costs (LCC)	Total life-cycle maintenance costs over a 50-year service life	High expenditures on recurring structural assessments, crack injection, and concrete cover replacement	Autogenous self-healing UHPC + SMA alloys + crystalline admixtures (CA)	20–35% reduction in life-cycle maintenance costs (LCC); autonomous crack closure of up to 90%, with structural stiffness recovery of up to 35%.

Continuation of Table 2.

Type of Advantage	Parameter	Traditional solutions	Implementation of New Technologies	Tangible operational and engineering benefits
Repair frequency	Traffic continuity maintenance and routine repairs	Disruptive, ad hoc repairs requiring lane restrictions or complete bridge closure	Encapsulation and bacterial biomineralization (MICP)	Autonomous crack healing (100–500 μm) without human intervention and without traffic disruption.
Construction and assembly time	Construction duration	Multi-week formwork erection, rebar fixing, and concrete curing	Robotic 3D printing (Additive Manufacturing)	Reduction of superstructure fabrication time to under 2 hours, elimination of formwork costs, and immediate on-site erection.
Environmental impact	Carbon footprint and chemical emissions	Petroleum-based chemical dependence, significant VOC emissions	Thermax bio-based plasticizers + SikaProof Eco-Line membranes	25–35% reduction in embodied carbon footprint; 80% decrease in VOC emissions; over 70% bio-based/renewable content in waterproofing.

Source of the table: compiled by the author based on analysis [3-14]

Consequently, the implementation of the aforementioned technologies—spatial optimization, green chemistry, and the active utilization of materials that extend the service life of engineering structures through autonomous self-healing—establishes a comprehensive ecosystem for constructing safe and environmentally friendly infrastructure. A critical challenge remains the thorough standardization of these processes and the adaptation of design codes and standards to accommodate the emerging capabilities of materials engineering.

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The authors of the III International Scientific and Practical Conference «Global scientific dialogue: challenges, innovations, and future horizons» were representatives of the following educational institutions:

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Scientific publications

Proceedings of the III International Scientific and Practical Conference
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(September 22–25, 2026)

UDC 01.1

ISBN – 979-8-90553-916-9

DOI – 10.46299/ISG.2026.2.3

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The recommended citation for this publication is: Ponochovnyi Y., Protas R. Modern materials and innovative technologies in bridge construction. Proceedings of the III International Scientific and Practical Conference. Hamburg, Germany. 2026. Pp. 15-22
URL: <https://isg-konf.com/global-scientific-dialogue-challenges-innovations-and-future-horizons/>