

Beyond Repair: A Critical Review of Smart, Sustainable, and AI-Driven Strengthening Techniques for Aging Civil Infrastructure

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Abstract: The durability and safety of civil infrastructure are progressively subjected to challenges posed by a range of factors, including aging, excessive utilization, environmental stressors, and natural disasters. Traditionally, efforts to strengthen structures have relied heavily on reactive and material-intensive solutions. However, recent developments signal a significant shift toward more intelligent, sustainable, and digitally informed approaches. This review comprehensively examines the evolving landscape of structural reinforcement techniques, tracing the movement from conventional methods to more advanced, adaptive systems. The analysis strongly emphasises evaluating structural performance through innovative means, highlighting the growing use of smart materials and the transformative role of digital tools and artificial intelligence (AI) in optimizing design and intervention strategies. These technological advances are enhancing efficiency and precision and enabling more predictive and responsive maintenance practices. The review considers aligning these emerging practices with broader sustainability and circular economy principles. It examines how strategies that prioritise material efficiency, reuse of existing components, and lifecycle-based planning can help mitigate the environmental impact of structural interventions. By integrating these dimensions, the paper underscores the potential of modern reinforcement techniques to support global ecological objectives while maintaining structural integrity. Moreover, the review outlines prospective directions for innovation, including AI-assisted co-design processes, the use of 3D printing technologies for customised retrofitting, and the application of bio-inspired adaptive systems. These forward-thinking concepts are presented as key enablers of a new generation of reinforcement strategies—ones that are robust, responsive, and ecologically conscious. Through a synthesis of current research and emerging opportunities, this study aims to inform and inspire the advancement of structural strengthening methods that are equipped to meet the complex challenges of the future built environment.

Keywords: Structural Strengthening, Smart Infrastructure, Sustainable Retrofit, Artificial Intelligence in Civil Engineering, and Circular Economy in Construction.

Abbreviations:

AI: Artificial Intelligence
FRPs: Fibre-Reinforced Polymers
SHM: Structural Health Monitoring
UHPC: Ultra-High-Performance Concrete

SMA: Shape Memory Alloys
RC: Reinforced Concrete
FEM: Finite Element Methods
FBG: Fibre Bragg Grating
EAPs: Electro-Active Polymers
DTs: Digital Twins
ML: Machine Learning
LCA: Life Cycle Assessment
GA: Genetic Algorithms
AM: Additive Manufacturing

I. INTRODUCTION

The built environment forms the physical backbone of societal development, with civil infrastructure, including bridges, highways, dams, and public buildings, serving critical roles in transportation, safety, and economic sustainability. Effective strengthening strategies become paramount as these structures age under the increasing demands of urbanisation, climate change, and evolving design standards. Globally, many infrastructure systems are operating beyond their intended service life. For example, over 42% of bridges in the United States are at least 50 years old, with more than 7.5% classified as structurally deficient as of 2023 [1]. The trend is similar in Europe and Asia, where ageing, fatigue, and environmental degradation are raising concerns about long-term serviceability and safety [2].

Traditional strengthening techniques such as steel jacketing, external post-tensioning, and epoxy injection have been used extensively. While these methods often deliver short- to medium-term improvements in load-carrying capacity and durability, they suffer from drawbacks including high labour demands, incompatibility with existing materials, and disruption to service during implementation [3]. Furthermore, many conventional methods lack adaptability, making them unsuitable for infrastructure exposed to complex, multi-hazard environments such as seismic events, corrosion-prone coastal zones, and high-fatigue transportation corridors.

Recent advancements in high-performance materials, structural health monitoring (SHM), and data-driven modelling are fundamentally transforming the landscape of infrastructure strengthening. Materials such as fibre-reinforced polymers (FRPs), ultra-high-performance concrete (UHPC), and shape memory alloys (SMAs) are enabling lightweight, durable, and corrosion-resistant retrofitting solutions [4]. At the same time, AI-driven assessment tools and digital twin technologies are providing real-time insights into structural condition [5], enabling preemptive

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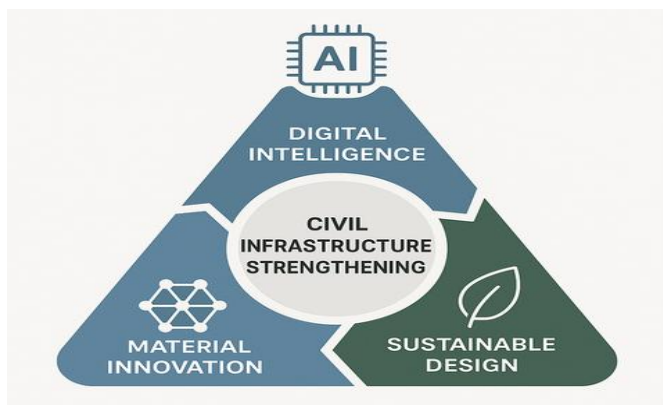
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strengthening interventions based on predictive analytics rather than reactive maintenance [6].

Moreover, the push for sustainable and circular solutions is reshaping how we approach strengthening. Emphasis is increasingly being placed on minimizing life-cycle carbon emissions, extending material reuse, and developing adaptable systems that can evolve with changing functional and environmental requirements [7]. This is especially relevant given the global commitment to decarbonising the construction industry and enhancing infrastructure resilience to climate-related risks.

Figure 1 illustrates the convergence of these emerging paradigms—innovative materials, AI integration, and sustainability—forming the foundation for a next-generation infrastructure-strengthening ecosystem.



[Fig.1: A Conceptual Framework Showing the Integration of Advanced Materials, AI-Driven Diagnostics, and Sustainability in the Future of Civil Infrastructure Strengthening]

This review critically examines the current and emerging techniques for strengthening civil infrastructure from a structural engineering standpoint. It identifies key advancements, ongoing challenges, and transformative trends shaping the future of resilient and adaptive infrastructure. Through a comprehensive assessment of legacy and state-of-the-art methods, this work aims to provide a strategic roadmap for integrating intelligent, sustainable, and performance-based strengthening approaches into mainstream engineering practice.

Table-I: Comparison of Traditional vs. Modern Strengthening Approaches

Criteria	Traditional Techniques	Modern Approaches
Materials	Steel plates, concrete jacketing	FRPs, UHPC, SMAs, bio-based composites
Durability	Moderate (corrosion-prone)	High (corrosion-resistant, self-healing potential)
Adaptability	Rigid, difficult to modify	Flexible, scalable, adaptive
Installation Impact	High (labour-intensive, disruptive)	Low (prefabricated, robot-assisted, rapid)
Monitoring Integration	Rare or absent	Integrated with SHM and sensing systems
Environmental Impact	High (energy-intensive, non-recyclable)	Low (sustainable, recyclable, low-carbon)
Intelligence/Automation	Absent	AI-driven, digital twin-supported

II. EVOLUTION OF STRENGTHENING TECHNIQUES

Civil infrastructure strengthening has undergone significant evolution over the past century, transitioning from rudimentary repairs to highly engineered and performance-based retrofitting solutions. This evolution reflects changes in material availability, construction technology, structural codes, and the rising demand for serviceability, resilience, and sustainability. The historical trajectory can be categorized into three main eras: traditional strengthening, composite material integration, and the emerging intelligent systems era.

A. Traditional Strengthening Methods

Initially, strengthening strategies were largely empirical and manually intensive. Techniques such as steel plate bonding, section enlargement (jacketing), and external post-tensioning dominated the 1950s to 1980s [8]. These methods aimed to restore or improve load-bearing capacity following visible deterioration or increased loading requirements.

For instance, concrete jacketing (Figure 2a) involved encasing existing structural members in additional layers of reinforced concrete to enhance strength and stiffness. Similarly, steel jacketing was used for columns and piers, particularly in seismic zones, to provide confinement and shear resistance. Although effective in the short term, these methods suffered from limitations such as increased dead loads, labour-intensiveness, extended downtime, and incompatibility with deteriorated or corroded substrates [9].

External post-tensioning of bridge girders and slabs also gained popularity, particularly in Highway Bridge strengthening, allowing for rapid stiffness recovery without internal alterations. However, issues such as tendon corrosion and anchor system failures emerged over time [10].

B. Composite Material Era

The 1990s and 2000s saw a paradigm shift with the introduction of fibre-reinforced polymer (FRP) composites. These materials—lightweight, corrosion-resistant, and easily installable—addressed many of the shortcomings of steel-based solutions [11]. FRP-based techniques include externally bonded laminates, near-surface mounted (NSM) bars, and FRP jacketing (Figure 2b).

Externally bonded FRP sheets have become the go-to method for strengthening concrete beams and columns, enhancing their flexural, shear, and confinement capacities with minimal geometric alteration. Despite their widespread use, FRPs have shown susceptibility to debonding, UV degradation, and limited fire resistance [12]. This led to innovations such as hybrid FRP-steel systems and the use of thermoplastic or mineral-based composites, which have improved performance in harsh environments.

Simultaneously, materials like ultra-high-performance fibre-reinforced concrete (UHPFRC) emerged as overlays or jackets for improving fatigue resistance and durability of bridge decks and piers [13]. UHPFRC offers exceptional compressive strength (≥ 150 MPa) and crack control, making it ideal for retrofitting applications subjected to dynamic or cyclic loads.



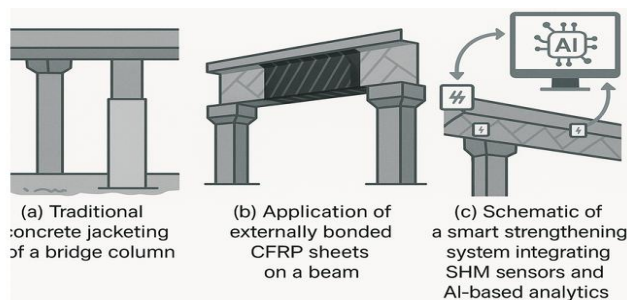
C. Toward Intelligent Strengthening Systems

The field has begun moving toward smart, data-driven, and sustainable strengthening systems in the last decade. The integration of sensors, innovative materials, and digital technologies enables not only structural enhancement but also real-time condition monitoring and adaptive performance tuning [14].

For instance, shape memory alloys (SMAs) offer self-centring capabilities after seismic events, making them suitable for strengthening bridges and high-rise structures in seismic-prone regions. Self-healing concrete, incorporating encapsulated healing agents or microbial additives, is also gaining traction for proactive durability strengthening [15].

Moreover, the emergence of digital twins and AI-driven modelling tools allows engineers to simulate deterioration patterns and virtually test strengthening strategies before physical application, optimizing material use and intervention timing [6].

Figure 2 illustrates the chronological evolution of strengthening approaches, reflecting a gradual shift from manual and material-heavy methods to intelligent, adaptive, and sustainable systems.



[Fig.2: (a) Traditional Concrete Jacketing of a Bridge Column; (b) Application of Externally Bonded CFRP Sheets on a Beam; (c) Schematic of a Smart Strengthening System Integrating SHM Sensors and AI-Based Analytics]

Table-II: Milestones in the Evolution of Structural Strengthening Techniques

Era	Techniques	Materials Used	Key Characteristics	Challenges
1950s – 1980s	Jacketing, Post-tensioning, Steel bracing	Concrete, Steel	High strength, easy to understand	Labour-intensive, corrosion, increased dead load
1990s – 2010s	FRP Wrapping, NSM, UHPFRC Overlays	CFRP, GFRP, UHPFRC	Lightweight, corrosion-resistant, fast retrofit	Fire sensitivity, cost, and bond reliability
2010s – Present	Smart Composites, AI-Enhanced Strengthening	SMAs, Self-healing concrete, AI	Adaptive, self-sensing, predictive maintenance	Technological complexity, integration challenges

III. STRUCTURAL PERFORMANCE EVALUATION

Evaluating the structural performance of strengthened systems is crucial to validate the effectiveness of retrofitting techniques, ensure adequate safety margins, and predict long-term behaviour under both service and extreme loading conditions. A combination of factors, including material

properties, interface behavior, load paths, environmental exposure, and the type of applied strengthening influences structural performance. This section reviews performance outcomes based on experimental research, numerical simulations, and field assessments, while also highlighting performance under multi-hazard loading scenarios.

A. Experimental Insights from Laboratory Studies

Controlled laboratory testing has been fundamental in understanding the mechanical and failure behavior of strengthened structural elements [16]. Tests on beams, columns, slabs, and joints retrofitted with FRPs, UHPFRC overlays, or steel jackets have revealed notable improvements in load-carrying capacity, ductility, and energy dissipation [11].

For example, flexural testing of reinforced concrete (RC) beams externally strengthened with carbon FRP (CFRP) sheets showed load capacity increases of 40–80%, with improved crack control and failure shifts from flexural to shear or debonding modes [17]. Likewise, column tests retrofitted with concrete or FRP jacketing demonstrated enhanced confinement, resulting in increased axial strength and ductility, particularly under cyclic loading [9].

UHPFRC strengthening, when applied as a tension zone overlay, significantly enhanced fatigue life in bridge deck elements by distributing stresses more uniformly and delaying crack propagation [18]. Table 3 summarises the key experimental findings for various strengthening approaches.

Table-III: Summary of Laboratory-Tested Performance Improvements with Common Strengthening Techniques

Strengthening Method	Target Element	Observed Improvement	Failure Mode	Key Reference
CFRP sheets (EB)	RC beams	+50–80% flexural capacity, better crack control	Debonding, shear failure	[17]
FRP jacketing	Columns	+60–100% axial load capacity, higher ductility	Buckling or FRP rupture	[9]
UHPFRC overlay	Bridge decks	+200% fatigue life, reduced crack width	Flexural cracking at the bond zone	[18]
Steel jacketing	RC columns	+50% strength and stiffness, good energy dissipation	Local buckling, corrosion risk	[19]
NSM CFRP strips	RC beams/slabs	+30–70% flexural capacity, durable bond behavior	Concrete cover spalling	[20] & [11]

B. Insights from Field Performance and Monitoring

While lab-scale studies provide critical data, real-world field performance is crucial for validating long-term efficacy. Numerous bridges and buildings have been retrofitted with FRPs, steel systems, or hybrid Systems, solutions, with long-term monitoring programs showing promising results.



The I-395 Bridge in Florida, strengthened with externally bonded CFRP sheets in 1997, remains in service with no significant signs of deterioration, as confirmed by ultrasonic and thermographic inspections over two decades [22]. Similarly, UHPFRC overlays on European bridge decks have demonstrated remarkable durability and fatigue resistance under traffic loads and freeze-thaw cycles for more than 15 years [21].

Advanced structural health monitoring (SHM) systems, incorporating fibre-optic sensors, strain gauges, and acoustic emission detectors, are increasingly used to evaluate in-service performance. These systems help detect early warning signs of bond failure, crack propagation, or material degradation, supporting data-driven maintenance.

C. Numerical Simulation and Finite Element Modelling

Computational simulations, particularly finite element methods (FEM), have become a powerful tool for performance evaluation, complementing experimental and field data. FEM enables a detailed examination of stress distributions, interface behaviours, and failure mechanisms under static, dynamic, and environmental loading conditions.

For example, numerical models have been used to predict the debonding behaviour of CFRP-strengthened beams using cohesive zone models, capturing the nonlinear interfacial slip and energy dissipation [23]. Advanced multi-scale simulations have also been applied to evaluate UHPFRC overlays under fatigue loading and thermal gradients [24].

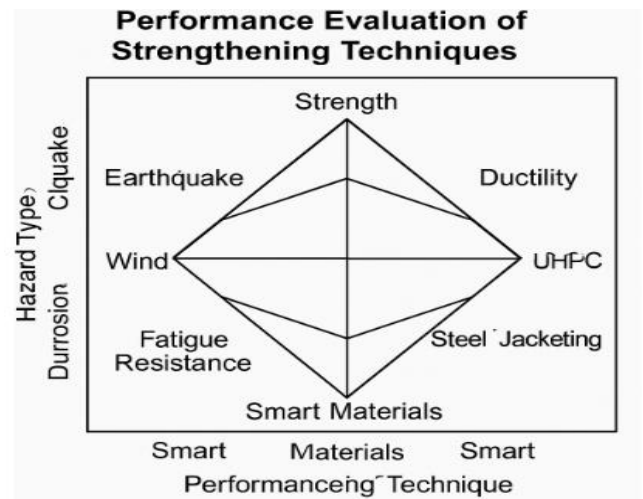
FEM also facilitates parametric studies to optimise design variables, such as FRP thickness, anchorage systems, and spacing of strengthening elements, reducing reliance on costly physical testing. The integration of FEM with AI algorithms and digital twin frameworks is paving the way for real-time structural performance prediction and decision-making [6].

D. Performance under Multi-Hazard Conditions

Modern infrastructure is increasingly expected to withstand multi-hazard scenarios, including seismic events, extreme weather, and sustained fatigue. Recent literature has focused on the structural performance under such complex loading conditions.

Seismic retrofitting, particularly of RC columns and beam-column joints using FRPs or steel jackets, has shown success in enhancing ductility and reducing inter-story drift demands [25]. Cyclic loading tests indicate that hybrid systems—such as FRP + SMA or FRP + UHPFRC—can offer superior resilience by combining energy dissipation with re-centring behaviour [26].

In coastal and marine environments, strengthening systems must endure chloride attack, corrosion, and impact loading. Protective coatings, corrosion-resistant FRPs, and UHPFRC are preferred for such applications, though performance remains sensitive to bond durability and thermal expansion mismatch [27].



[Fig.3: A Visual Summary Comparing Structural Performance Parameters]

IV. SMART STRENGTHENING SYSTEMS

The advancement of digital technologies, sensor integration, and adaptive materials has given rise to a new generation of innovative strengthening systems for civil infrastructure. These systems enhance structural performance and enable self-monitoring, self-adaptive, and even self-healing functionalities. The goal is to extend service life, reduce maintenance costs, and improve resilience, especially under complex or unpredictable loading scenarios.

Smart strengthening integrates multiple disciplines—material science, structural engineering, sensor technology, and artificial intelligence—into a cohesive system capable of detecting, responding to, and anticipating damage.

A. Sensor-Integrated Strengthening Systems

One of the earliest forms of smart strengthening involves embedding structural health monitoring (SHM) components within or onto strengthening materials. Fibre Bragg grating (FBG) sensors, strain gauges, accelerometers, and piezoresistive sensors are commonly integrated into FRP wraps, steel plates, or UHPFRC overlays to continuously monitor structural responses.

For instance, innovative CFRP laminates embedded with FBG sensors have been used to monitor strain development and detect early-stage debonding in retrofitted beams [28]. These sensors provide real-time feedback during service, enabling predictive maintenance and minimizing the need for intrusive inspections.

In bridge applications, long-span cable-stayed and suspension bridges are being retrofitted with sensor-integrated dampers and stay-cable strengthening systems, allowing for dynamic response tracking under traffic and wind loads [29].

B. Adaptive Materials in Smart Strengthening

Emerging materials that can change properties in response to stimuli redefine how structures are strengthened and maintained. Key among these are:

- i. Shape Memory Alloys (SMAs): These materials can undergo enormous



strains and return to their original shape upon heating. When used in strengthening systems—such as external reinforcements or connectors—they offer self-centring and energy dissipation properties ideal for seismic applications [26].

- ii. Electro-active Polymers (EAPs) and Piezoelectric Composites: These materials deform under electric fields, offering potential in vibration control and damage mitigation. Though still in experimental

phases, their integration with FRP systems is being explored [30].

- iii. Self-healing materials, including bio-based concrete and microcapsule-embedded UHPFRC, offer promising avenues for extending the durability of strengthened structures. For example, microbial concrete has been shown to heal cracks up to 0.8 mm wide over several wetting and drying cycles.

Table-IV: Emerging Smart Materials for Structural Strengthening Applications

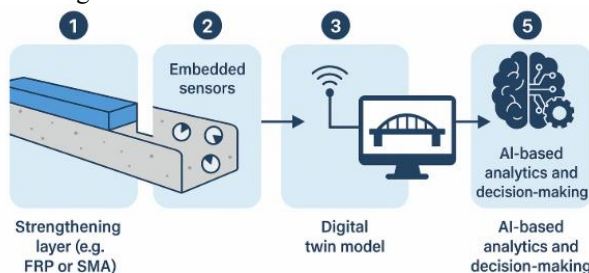
Material/System	Functionality	Applications	Advantages	Challenges
Shape Memory Alloys (SMA)	Self-centring, hysteresis damping	Seismic strengthening of frames and bridges	Energy dissipation, reusability	High cost, thermal activation needed
Fibre Bragg Grating (FBG)	Real-time strain and temperature sensing	Monitoring in FRP wraps and UHPFRC jackets	High precision, multiplexing capability	Fragility, embedding complexity
Piezoelectric FRPs	Vibration sensing and active control	Slabs, bridges, and dynamic structures	Dual function (sensing + actuation)	Low power output, integration issues
Self-healing UHPFRC	Crack sealing, durability improvement	Bridge decks, tunnel linings	Extended service life, autonomous repair	Long healing time, limited crack size

C. Digital Twin and AI-Augmented Strengthening Systems

The integration of digital twins (DTs)—virtual replicas of physical structures—with AI algorithms represents a frontier in smart strengthening. These systems synthesise real-time sensor data, finite element models, and historical performance data to simulate the current and future behaviour of structures continuously.

For example, an FRP-strengthened bridge pier can be digitally modelled with embedded strain data feeding into an AI model trained to predict fatigue life, detect anomalies, and recommend optimal repair interventions [6]. Such frameworks allow remote visualization, intervention planning, and sustainability evaluation.

Machine learning algorithms are also used to calibrate material degradation models, predict bond-slip behaviour, and optimize strengthening configurations based on uncertainty quantification [31]. These systems form a core part of next-generation infrastructure asset management when integrated with cloud-based dashboards.



[Fig.4: a Conceptual Diagram Showing the Components of a Smart Strengthening System: (1) Strengthening Layer (e.g., frp or Sma), (2) Embedded Sensors, (3) Data Acquisition and Transmission, (4) Digital Twin Model, and (5) ai-Based Analytics and Decision-Making]

D. Benefits and Limitations

Innovative strengthening systems offer several advantages:

- i. Real-time damage detection and localization
- ii. Reduced maintenance frequency and cost
- iii. Improved resilience under extreme events
- iv. Prolonged service life through proactive interventions

However, challenges remain. These include system complexity, high initial costs, data management issues, and gaps in standardisation for sensor calibration, data interpretation, and design integration. Moreover, field deployment in harsh environments often introduces durability concerns for embedded electronics.

V. AI AND DIGITALIZATION IN STRENGTHENING

The increasing complexity of civil infrastructure, combined with the urgent need for proactive and sustainable maintenance, has propelled the integration of Artificial Intelligence (AI) and digital technologies into the domain of structural strengthening. These advancements transform traditional retrofitting approaches into data-driven, intelligent frameworks that support automation, real-time decision-making, and lifecycle optimisation.

AI-driven strengthening solutions rely on a synergy of big data, digital twins, machine learning (ML), computer vision, and Internet of Things (IoT) technologies. Their application spans pre-strengthening diagnosis and design optimization to post-strengthening performance evaluation and predictive maintenance.

A. AI for Damage Detection and Condition Assessment

AI has revolutionised structural diagnostics by enabling the automated detection of damage, particularly with image-based or sensor-based inspection methods. Using deep learning, particularly convolutional neural networks (CNNs), researchers have trained models to detect surface cracks, delamination, corrosion, and other defects with remarkable accuracy [32].

For example, computer vision algorithms can process drone-captured images of bridge decks and identify spalling or surface defects before strengthening interventions. These systems reduce inspection time and labour while enhancing safety and objectivity.

Furthermore, anomaly detection models using SHM data (strain, acceleration, displacement) have been applied to assess performance changes in retrofitted structures, offering early warnings before critical failure occurs [33].

B. Machine Learning for Strengthening Design Optimization

ML techniques are increasingly used to optimize strengthening design parameters such as FRP layout, thickness, anchorage length, and composite type. Data-driven models learn from experimental databases or simulated datasets to predict structural response and recommend optimal strengthening schemes.

For example, support vector machines (SVM) and artificial neural networks (ANN) have been successfully trained to predict flexural capacity and debonding likelihood of FRP-strengthened beams under varying geometric and material conditions [34].

When combined with evolutionary algorithms such as genetic algorithms (GAs) or particle swarm optimization (PSO), ML models can explore large design spaces to find cost-effective and high-performance strengthening strategies for both individual components and entire structures.

Table-V: Applications of AI in Structural Strengthening

AI Method	Application	Benefits	Reference
CNN (Deep Learning)	Crack detection in RC elements	Fast, accurate, non-invasive	[32]
SVM & ANN	Capacity prediction of FRP-strengthened beams	Reduces design iterations, supports automation	[34]
LSTM (Time Series ML)	Predicting degradation trends from SHM data	Enables predictive maintenance	[33]
PSO & GA	Strengthening layout optimisation	Finds optimal trade-offs between cost & strength	[35]
Decision Trees & XGBoost	Classifying failure modes in retrofitted columns	High interpretability supports risk assessment	[36]

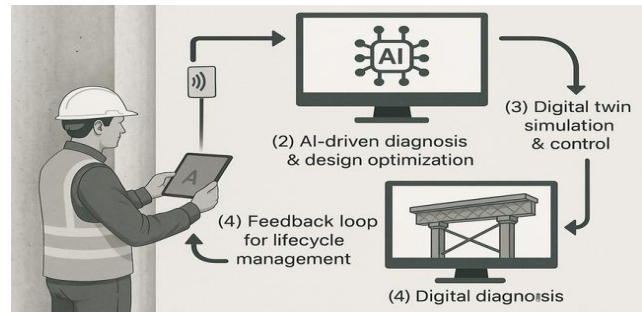
C. Digital Twins for Smart Strengthening Systems

The digital twin (DT) concept—a live digital replica of a physical structure—has gained traction in enhancing applications, particularly for large-scale infrastructure such as bridges and tunnels. A digital twin combines real-time data from sensors with physics-based models and AI-driven simulations to assess structural health and continuously inform decisions on strengthening.

In a strengthening context, a DT can:

- Simulate the effect of proposed retrofitting schemes before implementation.
- Predict the lifecycle performance of different materials under varying conditions.
- Monitor in-service behavior post-strengthening and recalibrate it using SHM feedback.

For example, [37] developed a DT system for a cable-stayed bridge retrofitted with CFRP, integrating FBG sensor data and FEM simulations. The model could detect strain anomalies and automatically suggest strengthening reinforcement if predicted stress exceeded thresholds.



[Fig.5: A Schematic Showing the Integration of AI and Digitalization in Strengthening Workflows: (1) Data Acquisition via SHM & Inspections → (2) AI-Driven Diagnosis & Design Optimization → (3) Digital Twin Simulation & Control → (4) Feedback Loop for Lifecycle Management]

D. Integration Challenges and Future Directions

While the potential of AI and digitalization in strengthening is vast, several technical and practical challenges must be addressed:

- Data quality and availability: Many AI models require large, labelled datasets for training, which are often lacking in infrastructure applications.
- Standardisation: Unified data protocols, model validation procedures, and interoperability standards are needed between platforms and tools.
- Trust and explainability: Engineers often demand interpretable models to ensure reliable safety-critical decisions.
- Cyber Security: The need for secure data exchange and digital infrastructure becomes paramount as systems become interconnected via IoT.

Future research is moving toward AI-integrated digital platforms that combine real-time data, structural simulation, and decision-making capabilities into unified tools for automated design, assessment, and strengthening.

VI. SUSTAINABLE AND CIRCULAR APPROACHES IN STRUCTURAL STRENGTHENING

Sustainability in civil infrastructure has evolved beyond minimising environmental impact to embracing circular economy principles, where resource reuse, material longevity, and minimal waste inform system-level decisions. In structural strengthening, this shift is manifested through the use of low-carbon materials, deconstruction-friendly designs, the reuse of existing members, and life-extension strategies. These approaches contribute to achieving the United Nations Sustainable Development Goals (UN SDGs), particularly SDG 9 (Industry, Innovation, and Infrastructure) and SDG 11 (Sustainable Cities and Communities).

Rather than merely reinforcing ageing structures, modern strengthening interventions are now expected to achieve more with less—less material, less energy, and less waste—while delivering greater durability, adaptability, and lifecycle value.

A. Low-Carbon and Recycled Strengthening Materials

The environmental impact of traditional strengthening materials, such as steel plates or epoxy-bonded FRPs, is



non-negligible due to their high embodied carbon and poor end-of-life recyclability. Consequently, sustainable alternatives are being explored, including:

- Basalt fibre-reinforced polymers (BFRPs) and natural fibre-reinforced polymers (NFRPs), derived from flax, hemp, or jute, offer lower environmental footprints than carbon or glass fibres [38].
- Geopolymer composites, which use industrial by-products like fly ash or slag, are gaining popularity as matrix materials in eco-friendly FRP systems [39].
- Second-generation CFRPS use recycled carbon fibres and reprocessed polymer matrices to retain mechanical performance while reducing emissions.

These materials are greener and often exhibit satisfactory mechanical properties and durability, particularly in terms of moisture resistance and UV stability.

Table-VI: Sustainable Strengthening Materials: Characteristics and Environmental Benefits

Material Type	Carbon Footprint	Key Benefits	Limitations
Basalt FRP	Medium–Low	Natural source, corrosion resistance	Slightly lower tensile strength than CFRP
Natural FRP (Flax, Jute)	Low	Renewable, biodegradable	Moisture sensitivity, durability issues
Geopolymer FRP	Very Low	Uses industrial waste, low-carbon binder	Bonding reliability is still under study
Recycled CFRP	Medium	Reduces landfill, retains fibre properties	Fibre alignment and length are variable

B. Reuse and Deconstruction for Circularity

A critical component of the circular economy in civil engineering is the reuse of structural members and design for deconstruction (DfD). As an alternative to demolition, DfD aims to ensure structural components can be disassembled, strengthened, and reused with minimal energy input.

Emerging research explores the reuse of steel beams, prestressed tendons, and even RC slabs from decommissioned bridges and buildings, with proper evaluation of fatigue damage and residual capacity [40]. Strengthening is vital here, as reused elements are often retrofitted with FRP wraps or UHPFRC jackets to compensate for degradation.

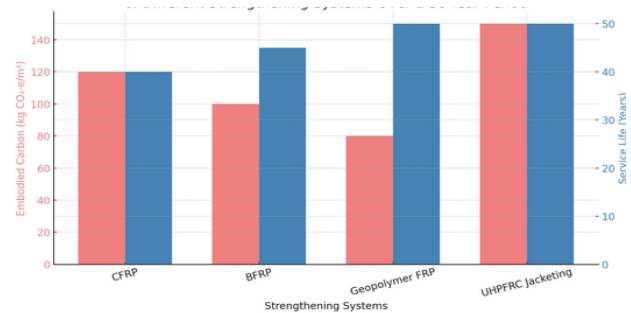
Strengthening systems themselves are being reimaged for disassembly, e.g. [41], bolted steel plates or mechanically anchored FRP strips, which can be detached and repurposed. This opens pathways for component leasing models, where strengthening materials are retrieved, refurbished, and reused elsewhere—a concept gaining traction in Europe.

C. Lifecycle Thinking in Strengthening Decisions

Modern strengthening design is increasingly informed by life cycle assessment (LCA), life cycle cost analysis (LCCA), and life cycle performance modelling to quantify sustainability. These tools help engineers compare the long-term environmental and economic impacts of various retrofitting options.

For instance, UHPFRC overlays, though material-intensive, can extend service life by decades with minimal maintenance,

making them cost-effective and carbon-efficient over a 50-year horizon [21]. Similarly, strengthening versus replacement decisions for bridge decks or columns are often guided by multi-criteria assessments that weigh durability, emissions, user impact, and circularity.



[Fig.6: A Comparative Graph Showing the Embodied Carbon and Service Life of Different Strengthening Systems: Conventional CFRP, BFRP, Geopolymer FRP, and UHPFRC Jacketing Over a 50-Year Period]

D. Policy, Certification, and Market Integration

Policy frameworks and certification systems also support the transition to sustainable strengthening practices. Standards such as EN 15804 for Environmental Product Declarations (EPDs) and emerging Circularity Indicators (CIs) enable benchmarking and third-party verification of material sustainability.

However, the practical integration of circular approaches in the field is still limited due to:

- Lack of design codes for reused materials
- Limited field data on the long-term performance of recycled or natural composites
- Uncertain market acceptance and supply chains for circular products

Pilot projects and government incentives are crucial for demonstrating feasibility, generating data, and fostering industry confidence in circular strengthening solutions.

VII. FUTURE RESEARCH AND INNOVATION DIRECTIONS

The landscape of structural strengthening is rapidly evolving, driven by the need for resilient, adaptive, and sustainable infrastructure systems. Future research must transcend incremental improvements and embrace interdisciplinary innovation as the sector integrates digital intelligence, green materials, and circular design. This section outlines strategic directions where transformative advances are expected in the coming decades.

A. Adaptive and Self-Responsive Strengthening Systems

Emerging research envisions adaptive structures that can autonomously respond to environmental loads, structural degradation, or seismic events. Integrating innovative materials, such as shape memory alloys (SMAs), electroactive polymers, and self-healing composites, into strengthening systems enables real-time stiffness modulation and damage recovery.

For instance, SMA-based bracing or reinforcement can provide re-centring capacity

after earthquakes, reducing residual drift in RC frames. Similarly, self-healing UHPFRC incorporating microcapsules or bacterial agents offers the potential to close microcracks, thereby prolonging durability with minimal intervention.

Future Research Needs:

- i. Development of cost-effective, large-scale deployable innovative strengthening materials
- ii. Integration of embedded sensing and actuation for autonomous feedback control
- iii. Long-term durability testing in aggressive environments (marine, seismic, freeze-thaw)

B. AI Co-Design and Generative Engineering

Next-generation strengthening design may be led by AI-assisted generative frameworks, where algorithms synthesise optimal retrofit strategies that consider performance, cost, constructability, and carbon footprint. Engineers could use reinforcement learning, Bayesian optimization, and topology-informed ML to explore vast design spaces beyond conventional human limits.

Furthermore, co-design platforms that integrate structural FEM simulations, environmental assessments (LCA), and constructability metrics could enable engineers to collaboratively iterate on strengthening concepts in digital sandbox environments, thereby expanding both creativity and efficiency.

Future Research Needs:

- i. Development of explainable AI models tailored for structural retrofitting
- ii. Integration of AI tools with BIM, digital twins, and IoT-enabled SHM platforms
- iii. Creation of open-access datasets for training ML models on structural repair performance

C. 3D Printing and Digital Fabrication for Retrofit Components

The integration of additive manufacturing (AM) in construction, particularly for retrofit elements, allows for the fabrication of geometry-specific jackets, modular strengthening connectors, or tailored FRP shells directly on site. 3D printing using fibre-reinforced thermoplastics, cementitious composites, or eco-geopolymers opens new pathways for non-invasive and efficient strengthening, especially in complex geometries or heritage structures.

Researchers have explored robotic shotcrete printing, which enables layered application of high-performance repair mortars for bridge piers and retaining walls. Other work investigates custom-fitted composite wraps produced off-site via thermoplastic forming for structural rehabilitation.

Future Research Needs:

- i. Material behaviour modelling for printed strengthening elements under multiaxial loads
- ii. Hybrid digital fabrication combining prefabrication and in-situ extrusion
- iii. Field validation of robotic retrofit solutions in real structures

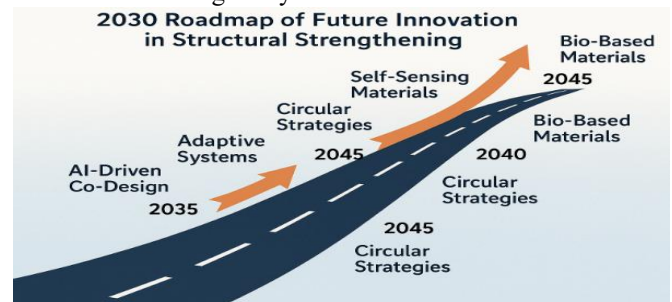
D. Circular and Bio-Inspired Strengthening Design

Nature offers a blueprint for resilient and resource-efficient systems. Drawing from shells, trees, or cellular structures, bio-inspired strategies can guide the development of high-strength, lightweight, and adaptive strengthening configurations. In parallel, integrating circular design principles at the early stage ensures that materials and systems are recoverable, reusable, and renewable.

Future structural components may exhibit cradle-to-cradle design, where strengthening elements are tagged, tracked, and reintegrated into the built environment after deconstruction. Digital passports and blockchain-backed lifecycle traceability are poised to play a role in managing component reusability and provenance.

Future Research Needs:

- i. Computational modelling of bio-inspired strengthening geometries
- ii. Standardization for reusable strengthening elements and lifecycle tracking
- iii. Policy integration and economic models for circular retrofitting ecosystems



[Fig.7: A Roadmap of Future Innovation in Structural Strengthening: From AI-Driven Co-Design and Adaptive Systems to bio-Inspired and Circular Strategies (2025–2050 Timeline)]

E. Resilience and Multi-Hazard Adaptation

As infrastructure faces compound risks from climate change, ageing, earthquakes, and flooding, future strengthening systems must ensure multi-hazard resilience. Rather than single-threat designs, integrated solutions combining energy dissipation, thermal protection, and corrosion resistance are essential.

Hybrid retrofitting schemes—e.g., combining FRP wrapping for corrosion control with SMA bracing for seismic resilience—are gaining attention. Additionally, the evaluation of strengthening systems must now consider recovery time, social resilience, and environmental co-benefits, moving beyond classical performance metrics.

Future Research Needs:

- i. Multi-hazard performance modelling and probabilistic risk assessment
- ii. Life-cycle-based resilience quantification and optimization
- iii. Integration of social and environmental resilience into retrofit strategies

Ultimately, the future of structural strengthening lies at the confluence of intelligent design,



sustainable materials, and system-level thinking. The field can move toward autonomous, adaptive, regenerative infrastructure solutions by fostering collaboration between structural engineers, material scientists, data scientists, and environmental experts. Strategic investment in experimental validation, standardization, and open innovation platforms will be crucial to translate these visionary concepts into practice—enabling infrastructure to last longer and evolve, heal, and sustainably serve future generations.

VIII. CONCLUSION

The strengthening of civil infrastructure is positioned at a pivotal juncture, where the pressing need for restoration converges with opportunities for innovation. While the past decades have witnessed significant progress in techniques and materials, future strengthening demands a more holistic and forward-thinking approach that enhances structural performance and supports long-term sustainability, digital integration, and social resilience.

This review has traced the progression of strengthening strategies from traditional reinforcement to the integration of innovative sensing, AI-based decision-making, and sustainable materials. It has highlighted how structural performance evaluation continues to evolve through advanced modelling and real-time monitoring, and how intelligent systems are making infrastructure increasingly autonomous and responsive. At the same time, the rise of circular economy principles and eco-conscious design introduces new responsibilities and possibilities for engineers to reduce waste and optimize lifecycle outcomes.

Innovation will hinge on interdisciplinary collaboration, combining structural engineering with materials science, data analytics, and systems thinking. Research must address persistent gaps in the scalability, durability, and standardisation of emerging solutions. At the same time, policy frameworks and funding mechanisms must evolve to support experimentation and adoption at a larger scale.

In conclusion, the future of civil infrastructure enhancement lies not only in strengthening structures but also in making them more innovative, more sustainable, and adaptable, thereby preparing them to meet the complex demands of a changing world.

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