

Advances in Bridge Design and Construction: Technologies and Applications

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1. Introduction

Bridges are critical elements of transportation networks, which, in turn, play a crucial role in the development of communities, cities, and nations. Throughout human history, the design and construction of bridges have represented the technological development of countries and are points of pride. With the Industrial Revolution, and especially after the Second World War, the construction of bridges experienced a significant boom in all industrial countries. These bridges, built 50 to 75 years ago, have reached their useful lifespan and must be reinforced, rehabilitated, and sometimes monitored in real time while awaiting replacement [1]. Furthermore, the rehabilitation or reconstruction of bridges is subject to climate change and new, more restrictive seismic requirements [2]. To meet the aforementioned needs and properly design and build a new generation of bridges, researchers worldwide are working hard at developing innovative technologies and materials that help realize high-performance and durable bridges with full respect for the environment [3].

In this context, the Special Issue “Advances in Bridge Design and Construction: Technologies and Applications” was launched to showcase state-of-the-art developments, practical applications, and visionary research in bridge engineering. This Special Issue aimed to gather contributions from academic researchers and practicing engineers addressing innovative solutions and breakthroughs across several dimensions of bridge design, construction, maintenance, retrofitting, and monitoring. The theme of this Special Issue was built around addressing emerging challenges, including structural deterioration in aging infrastructure, seismic resilience, the integration of advanced materials like CFRP and GFRP, real-time health monitoring, digital construction techniques such as 3D printing, and environmentally responsible approaches involving recycled materials. These diverse yet interconnected research domains reflect the evolving multidisciplinary nature of modern bridge engineering. A notable observation is the increasing convergence between traditional structural engineering practices and modern technologies such as artificial intelligence, optimization algorithms, and digital fabrication. Furthermore, sustainability is no longer a peripheral concern; it has become central to the bridge design philosophy. Simultaneously, emphasis on resilience, particularly seismic resistance and redundancy in structural systems, highlights a shift toward proactive rather than reactive engineering strategies.

This Special Issue successfully brings together 10 high-quality contributions from various parts of the world, each addressing critical and timely topics. While the articles offer depth in their respective focuses, collectively they bridge critical gaps in understanding



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and provide actionable insights for practitioners, policymakers, and researchers alike. Beyond summarizing existing knowledge, the published works point to future directions and research needs in areas such as AI-based design, advanced construction methods, performance-based seismic assessment, hybrid material applications, and sustainable lifecycle practices.

As guest editors, we are pleased to observe how the contributions in this issue align with the overarching goals of enhancing the performance, longevity, and environmental compatibility of bridge infrastructure. This Special Issue not only reinforces the significance of multidisciplinary collaboration in addressing engineering challenges but also lays a strong foundation for subsequent research and innovation.

2. An Overview of Published Articles

This section provides a concise summary of the ten published contributions, highlighting the motivation, methods, and key findings of each study. Contribution (1) is titled *Ultimate Capacity of a GFRP-Reinforced Concrete Bridge Barrier–Deck Anchorage Subjected to Transverse Loading*. This study addresses a practical challenge in bridge safety, which is barrier anchorage design, especially when using non-corrosive materials such as Glass Fiber-Reinforced Polymer (GFRP) bars. The research employed large-scale experimental testing to evaluate the transverse capacity of GFRP-reinforced barrier–deck anchorage systems. The outcomes offer critical insights for engineers seeking to replace traditional steel bars with GFRP bars in bridge safety systems, especially for environments prone to corrosion.

Contribution (2) is titled *Influence of Girder Flaring on Load Effect in Girders of Composite Steel Bridges*. This analytical study investigates the influence of girder flaring on internal force distribution. Girder flaring is a geometric feature often required due to alignment constraints. Using finite element analysis and parametric modeling, the authors quantified the amplified stresses and redistribution effects caused by varying degrees of flaring. The findings emphasize the need for more refined design practices in composite girder bridges where non-parallel girder configurations may lead to unexpected stress concentrations.

Contribution (3) is titled *Neural Network-Based Prediction of Amplification Factors for Nonlinear Soil Behaviour: Insights into Site Proxies*. Geotechnical input remains a crucial factor in bridge design, particularly for seismic performance assessment. This study applies machine learning, specifically neural networks, to predict amplification factors related to nonlinear site responses. The authors utilize a database of numerical simulations to train models based on site proxy parameters. The approach enhances accuracy over traditional empirical equations and has implications for bridge site characterization in seismic zones.

Contribution (4) is titled *Construction Control Technology and Monitoring Analysis of Walking Incremental Launching Construction of Small-Curvature Steel Box Girder Bridges Across Expressways*. Incremental launching is an increasingly popular bridge construction method, but applying it in curved steel box girders presents unique challenges. This contribution reports on a real-world application in China, analyzing construction control methods and monitoring techniques used in the field. Data from sensors and deflection monitoring systems were integrated with theoretical predictions to ensure the geometric precision and safety of the launched structure. The study highlights advancements in real-time construction monitoring and adaptive control strategies.

Contribution (5) is titled *Seismic Design and Ductility Evaluation of Thin-Walled Stiffened Steel Square Box Columns*. Bridge piers with stiffened steel box sections are promising for seismic applications due to their high ductility and energy dissipation. This

paper presents a comprehensive numerical study of their seismic performance under varying geometries and loading conditions. A design-oriented framework for assessing ductility and failure modes was proposed, offering guidelines for seismic-resistant bridge design using steel columns. The study contributes to the performance-based seismic design of bridge substructures.

Contribution (6) is titled Efficient Design Optimization of Cable-Stayed Bridges: A Two-Layer Framework with Surrogate-Model-Assisted Prediction of Optimum Cable Forces. Cable-stayed bridges are complex structures where optimization of cable forces is critical. This study proposes a two-layer optimization framework combining finite element modeling with surrogate modeling and machine learning to expedite the search for optimum cable forces. The framework reduces computational demand while maintaining accuracy, making it applicable to large-scale, practical bridge projects. The integration of AI into structural optimization exemplifies the future of computational bridge engineering.

Contribution (7) is titled 3D-Printed Concrete Bridges: Material, Design, Construction, and Reinforcement. Additive manufacturing is making its way into civil infrastructure. This review article provides an in-depth synthesis of 3D printing technologies applied to concrete bridges, covering material properties, design considerations, structural performance, and reinforcement strategies. The paper identifies current limitations, such as weak interlayer bonding and reinforcement integration, and outlines potential directions for future research. It serves as a roadmap for the gradual adoption of 3D printing in bridge construction.

Contribution (8) is titled Transition Effects in Bridge Structures and Their Possible Reduction Using Recycled Materials. Bridge transitions (e.g., between approach slabs and superstructures) often suffer from differential settlement and durability issues. This research explores the use of recycled materials, particularly rubber-modified backfill, to improve long-term performance. Laboratory testing and numerical analysis showed enhanced energy absorption and reduced stiffness contrast at transitions. The use of recycled materials contributes to both sustainability and functional performance, reflecting a growing trend in eco-conscious engineering.

Contribution (9) is titled The Seismic Behavior of Rectangular Concrete-Encased Steel Bridge Piers: A Review. Concrete-encased steel (CES) members combine the advantages of both materials and have demonstrated excellent seismic resilience. This paper provides a comprehensive literature review on CES bridge piers, focusing on their hysteretic behavior, failure mechanisms, and analytical modeling. The authors identify research gaps in cyclic loading behavior, confinement effects, and design codes. This review highlights the potential of CES piers in seismic bridge design and recommends further experimental and numerical research.

Contribution (10) is titled Retrofitting of Steel Structures with CFRP: Literature Review and Research Needs. Fiber-reinforced polymer (FRP) composites are widely used for retrofitting concrete structures, but their application to steel bridges is less mature. This review summarizes existing studies on CFRP retrofitting of steel members, focusing on adhesion mechanisms, fatigue performance, and environmental durability. The authors propose a research agenda addressing interface modeling, field validation, and long-term behavior. The article offers a foundation for expanding CFRP applications in steel bridge rehabilitation.

3. Conclusions

The contributions in this Special Issue represent a robust cross-section of the latest developments in bridge engineering, combining material innovation, computational advancements, construction techniques, and sustainability considerations. While each study

targets a specific aspect of bridge design and construction, together they form a comprehensive response to the multifaceted challenges facing modern bridge infrastructure.

3.1. Key Outcomes and Advances

1. **Material Innovation:** Several articles emphasize the shift toward non-traditional materials. GFRP and CFRP (Contributions 1 and 10) offer promising alternatives to traditional steel, especially in corrosive environments and retrofitting applications. The incorporation of recycled and sustainable materials (Contribution 8) further reinforces the environmental responsibility now central to infrastructure design.
2. **Seismic Resilience and Structural Optimization:** Contributions 5 and 9 present advances in understanding seismic behavior and design of bridge substructures. These studies, combined with machine learning-based geotechnical characterization (Contribution 3), offer a pathway toward more resilient and site-specific seismic design practices.
3. **Digital Design and Construction Technologies:** Digital tools are transforming bridge design and analysis. The surrogate modeling and optimization techniques for cable-stayed bridges (Contribution 6) and the application of neural networks for geotechnical modeling (Contribution 3) point to the future of AI-assisted engineering. Moreover, the article on 3D printing (Contribution 7) pioneers the fusion of digital design with physical construction.
4. **Construction Monitoring and Adaptive Control:** Contributions 4 and 2 emphasize the role of construction technology and monitoring in ensuring build quality. As construction becomes more complex, the integration of real-time data and intelligent control methods will be vital in reducing risk and improving precision.
5. **Retrofitting and Lifecycle Management:** With many existing bridges aging beyond their design life, the importance of retrofitting technologies cannot be overstated. Contributions 9 and 10 address these needs by reviewing and proposing advancements in seismic retrofitting and CFRP reinforcement.

3.2. Bridging the Gap and Future Directions

Despite the progress highlighted in this Special Issue, several research gaps persist. Field validation of novel materials and methods remains a pressing challenge. Long-term performance data, especially in aggressive environments, is critical for mainstream adoption [4]. Additionally, while digital tools offer promising capabilities, their integration into daily engineering practice requires user-friendly interfaces, standardized workflows, and training. The bridge engineering community must also continue advancing performance-based design frameworks that consider not only strength but also durability, serviceability, and sustainability throughout the lifecycle [5]. There is a growing need for integrated approaches where structural, geotechnical, material, and construction perspectives are unified in decision-making.

This Special Issue provides a timely and insightful contribution to the field of bridge engineering. It demonstrates that the convergence of new materials, advanced analytics, and innovative construction methods is no longer aspirational, as it is actively shaping the present and future of bridge design and construction. We hope that the insights offered here will inspire further research, collaboration, and practical implementation that advance the state-of-the-art and state-of-practice in bridge engineering worldwide.

Conflicts of Interest: The authors declare no conflicts of interest.

List of Contributions:

1. Dervishhasani, G.; Sennah, K.; Afefy, H.M.; Diab, A. Ultimate Capacity of a GFRP-Reinforced Concrete Bridge Barrier–Deck Anchorage Subjected to Transverse Loading. *Appl. Sci.* **2025**, *15*, 7771. <https://doi.org/10.3390/app15147771>.
2. Hraib, F.; Tabsh, S.W. Influence of Girder Flaring on Load Effect in Girders of Composite Steel Bridges. *Appl. Sci.* **2025**, *15*, 4674. <https://doi.org/10.3390/app15094674>.
3. Boudghene Stambouli, A.; Guizani, L. Neural Network-Based Prediction of Amplification Factors for Nonlinear Soil Behaviour: Insights into Site Proxies. *Appl. Sci.* **2025**, *15*, 3618. <https://doi.org/10.3390/app15073618>.
4. Huang, H.; Xue, X.; Ma, H.; Zhou, Z.; Dou, J.; Yang, H.; Guo, E.; Ma, J. Construction Control Technology and Monitoring Analysis of Walking Incremental Launching Construction of Small-Curvature Steel Box Girder Bridges Across Expressways. *Appl. Sci.* **2025**, *15*, 585. <https://doi.org/10.3390/app15020585>.
5. Njiru, M.; Mamaghani, I.H.P. Seismic Design and Ductility Evaluation of Thin-Walled Stiffened Steel Square Box Columns. *Appl. Sci.* **2024**, *14*, 8554. <https://doi.org/10.3390/app14188554>.
6. Ma, Y.; Song, C.; Wang, Z.; Jiang, Z.; Sun, B.; Xiao, R. Efficient Design Optimization of Cable-Stayed Bridges: A Two-Layer Framework with Surrogate-Model-Assisted Prediction of Optimum Cable Forces. *Appl. Sci.* **2024**, *14*, 2007. <https://doi.org/10.3390/app14052007>.
7. Miri, Z.S.; Baaj, H.; Polak, M.A. 3D-Printed Concrete Bridges: Material, Design, Construction, and Reinforcement. *Appl. Sci.* **2025**, *15*, 3054. <https://doi.org/10.3390/app15063054>.
8. Spyrowski, M.; Ostrowski, K.A.; Furtak, K. Transition Effects in Bridge Structures and Their Possible Reduction Using Recycled Materials. *Appl. Sci.* **2024**, *14*, 11305. <https://doi.org/10.3390/app142311305>.
9. Moradian, M.; Hassan, M. The Seismic Behavior of Rectangular Concrete-Encased Steel Bridge Piers: A Review. *Appl. Sci.* **2024**, *14*, 6627. <https://doi.org/10.3390/app14156627>.
10. Delzende Moghadam, M.; Fathi, A.; Chaallal, O. Retrofitting of Steel Structures with CFRP: Literature Review and Research Needs. *Appl. Sci.* **2024**, *14*, 5958. <https://doi.org/10.3390/app14135958>.

References

1. Statistics Canada. Inventory of Publicly Owned Bridge and Tunnel Assets, Infrastructure Canada. Government of Canada, 2018. Available online: <https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3410007801> (accessed on 31 July 2025).
2. Qiu, Z.; Prabhakaran, A.; Su, L.; Zheng, Y. Performance-based seismic resilience and sustainability assessment of coastal RC bridges in aggressive marine environments. *Ocean. Eng.* **2023**, *279*, 114547. [[CrossRef](#)]
3. Tan, X.; Mahjoubi, S.; Zhang, Q.; Dong, D.; Bao, Y. A framework for improving bridge resilience and sustainability through optimizing high-performance fiber-reinforced cementitious composites. *J. Infrastruct. Preserv. Resil.* **2022**, *3*, 18. [[CrossRef](#)]
4. Lamei, T.; Abdel-Rahim, A.; Ibrahim, A. Development of performance-based deterioration models for bridge components. *Innov. Infrastruct. Solut.* **2025**, *10*, 230. [[CrossRef](#)]
5. Zhao, X.L.; Li, W.; Stanbrook, J. A Framework for the Integration of Performance Based Design and Life Cycle Assessment to Design Sustainable Structures. *Adv. Struct. Eng.* **2014**, *17*, 461–470. [[CrossRef](#)]

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