Application of Overall Design Technology for Municipal Bridges under Complex Construction Conditions

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Abstract: Municipal bridge projects in urban core areas and along river channels face multiple challenges, including complex geological conditions, tight construction sites, sensitive traffic organization, and strict ecological protection and emission standards. Traditional design concepts, with structural safety as the sole goal, struggle to fully meet the comprehensive goals of safety, economy, and environmental protection. This study, focusing on a 26.7-kilometer-long urban expressway viaduct project, developed an integrated technical model combining structural mechanics analysis, prefabricated construction, green construction assessment, and life cycle costing. Life cycle costing and high-performance fiber-reinforced cementitious composites were incorporated into the overall design technology system. A standardized internal force and deflection calculation formula, a carbon emission accounting model based on emission factors, and a life cycle cost present value analysis model were constructed. Combined with prefabricated construction and HPFRCC key node strengthening measures, the design schemes of municipal bridges under complex construction backgrounds were compared and their effectiveness tested. The prefabricated scheme can shorten the construction period of the main project from 300 days to 105 days, a reduction of about 65%. The traffic closure time was shortened from 180 days to 60 days, a reduction of 67%. Carbon emissions were reduced by 29%, from 1.20 tons per kilometer to 0.85 tons per kilometer. The LCC curve showed a turning point in economic benefits in the 7th to 9th year of service. If the crack initiation stress of HPFRCC is increased to 14MPa, its toughness index will increase to 83%, effectively reducing tensile damage. The constructed comprehensive technical route of "life cycle, digital twin, prefabrication, and high-toughness materials" provides a simulatable and popularizable practical guide for the design, construction, and maintenance of municipal bridges in urban core areas and geologically complex environments.

1. Introduction

With rapid urbanization, municipal bridge construction is gradually moving beyond the singular focus on structural safety and construction speed, entering a new stage of comprehensive optimization focused on sustainable development and full lifecycle performance. This is especially true in key areas where ancient cities and rivers converge. Projects in core areas such as old urban areas and cross-river passages generally face numerous constraints, including complex geological conditions, dense underground pipelines, narrow working spaces, and extremely sensitive traffic organization. These projects must cope with multiple challenges, including construction interference control, environmental emission compliance, social cost management, and external risks such as extreme climate and earthquakes. Traditional design models prioritize structural safety and single-time investment. Against this backdrop, these designs face challenges such as extended project duration, increased carbon emissions, high operation and maintenance costs, and subsequent updates and maintenance, making it impossible to achieve a balance across the entire lifecycle of "construction-operation-update."

In today's complex construction environment, the overall design of municipal bridges urgently requires the adoption of multi-faceted, systematic technological advancements. Prefabricated and modular construction methods, relying on factory prefabrication and rapid on-site assembly, effectively shorten critical construction phases, reduce traffic closures, and minimize construction

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disruptions. This system, combined with life cycle cost (LCC) and carbon emissions (LCA) calculations, provides quantitative support for solution selection and economic and environmental balance. This composite material exhibits excellent toughness and crack control properties, effectively improving the structure's safety margin under earthquake and fatigue loads. Recently introduced technologies such as digital twins, BIM and GIS integration, intelligent monitoring, and drone inspections are providing new tools and data foundations for the comprehensive optimization of bridge construction and operation.

2. Related Literature Review

Zheng et al. comprehensively reviewed the innovative practices of the Pingnan Third Bridge in the fields of planning, construction and management, and the significance of comprehensive technology integration in the construction of super-large bridges [1]. Wei et al. critically analyzed the current application status of BIM and GIS in bridge engineering, and the introduction of information technology has significantly enhanced the sophistication of bridge design and operation and maintenance [2]. Li et al. further explored the application of information technology in the field of civil engineering, providing a technical basis for the full-stage management of bridges [3]. Omrany et al. conducted a detailed analysis of the application trends and difficulties of digital twin technology in architecture and construction from the perspective of implementation status and architecture. Digital twin technology is one of the key means of intelligent construction and operation and maintenance [4]. Choi et al. summarized the application of drone technology in the field of construction monitoring, and achieved high efficiency of safety inspection and data collection in complex working conditions. In the field of infrared thermal imaging technology [5], Kim et al. comprehensively reviewed the latest research trends in building diagnosis and condition monitoring, and built a technical platform for early warning of structural diseases [6]. Using the fuzzy hierarchical analysis method, Yang et al. investigated the safety factors of municipal roads underpasses of existing bridges, highlighting the necessity of implementing detailed safety evaluation in complex traffic situations [7]. Gó recki et al. analyzed the decision-making issues of bridge construction in the implementation of sustainable development strategies, emphasizing the core significance of environmental and social factors in engineering decision-making [8]. Hu et al. explored the application potential of digital twins and related technologies in the construction field from the perspective of Industry 4.0, providing a key reference for building a comprehensive system for intelligent municipal bridge design [9]. The research consistently shows that in a complex construction environment, structural safety, digital management, green construction and full life cycle cost control should be mutually infiltrated, which has laid a solid theoretical and practical foundation for the systematic research of the overall design technology of municipal bridges. The necessity of the comprehensive technical route proposed in this study has been further emphasized [10].

3. Project Overview

This project is carried out for a certain city expressway viaduct construction project, with a total length of 26.7 kilometers. The design speed of the road surface is 80 kilometers per hour. It has six lanes in two lanes and the maximum cross-sectional width of the main bridge is 150 meters. It starts from the western industrial area of the city, passes through the old city, and connects with the eastern expressway hub. There are 6 interchanges and 24 ramps along the line. The bridge length accounts for 82% of the line. There are dense underground pipelines along the line. The existing road traffic volume is large. The average width of the working space is only 18 meters. The surface geological composition is mainly silty clay, partially interspersed with pebble layers, and the lower layer is weathered sandstone. The groundwater level is measured at about 2.5 meters.

Adhering to the principle of "non-stop construction" and stringent environmental requirements (noise levels below 65 decibels, dust concentrations not exceeding 150 mg/m³, and wastewater COD values less than 100 mg/L), a comprehensive comparison of traditional cast-in-place and

prefabricated low-carbon construction techniques was conducted. The construction technology, centered on on-site rebar tying and formwork erection, resulted in a lengthy construction phase and significant traffic impact. The scheme utilized factory-prefabricated components, with on-site assembly and construction. This approach, along with segmented operations, nighttime construction schedules, and traffic diversions, achieved dynamic traffic diversion on the main arterial road and enhanced the structure's durability under seismic and fatigue conditions. HPFRCC local reinforcements were embedded in the negative moment zones of the continuous beams, the crossbeams at the top of the piers, and the tensile zones of the bridge deck. The structure was designed for a compressive strength of 120 MPa and a maximum tensile strain of 3.5%. See Figures 1 and Table 1 for details.

Table 1 Main engineering parameters

project	Value/Range	Remark
Total route length (km)	26.7	West City-East City Expressway
Bridge ratio (%)	82	Including main bridge, ramp and elevated section
Maximum span (m)	150	X River Main Bridge Steel-Concrete Continuous Beam
Design speed (km/h)	80	Urban expressway standards
Lane layout	Six lanes in both directions	Including emergency lane
Number of interchanges	6	Multi-node composite type
Average construction width (m)	18	The narrowest part of the old town is about 12 m
Groundwater level (m)	2.5	±0.5 m due to seasonal influence
Design reference period (years)	100	Structural durability goals
Earthquake fortification intensity	7 degrees	Peak acceleration 0.15g
Main structural materials	C60 concrete, HPFRCC	HPFRCC for focal enhancement
Prefabricated component types	Box beam, cap beam, bridge deck	Factory standardized production
Noise control requirements during construction period	<65 dB(A)	Nighttime construction requires additional noise reduction measures
Dust concentration control during construction period	<150 mg/m³	Setting up spray and fencing

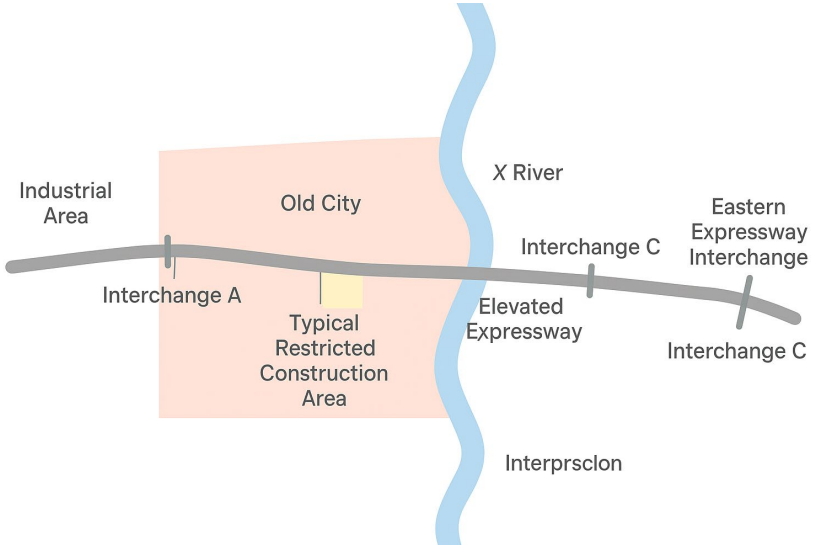

Figure 1 Project layout plan

4. Application of overall design technology for municipal bridges under complex construction conditions

4.1 Rapid estimation and verification of structural internal forces and deflections

To address the specific challenges of the narrow working area in the old city and the river

construction section, a simply supported equivalent model was used to conduct a rapid assessment of key spans during the schematic design phase. This was followed by a refined finite element review. Taking an equivalent simply supported box girder with a span of L as the object, and subject to the uniformly distributed load q, which is a combination of dead and live loads, the maximum bending moment, support shear force, and mid-span deflection of the beam were calculated as follows:

$$M_{\max} = \frac{qL^2}{8}, \quad V_{\max} = \frac{qL}{2}, \quad w_{\max} = \frac{5qL^4}{384EI} \tag{1}$$

In the formula, E the elastic modulus of the material is defined, I which corresponds to the moment of inertia of the section. The 150-meter section with the largest span in this project is considered as the key section. According to the structural dimensions and material parameters, and $M_{\max}$ are $w_{\max}$ calculated. The section strength and the ultimate deflection value of normal use are verified based on this data. A continuous system and construction stage model is formed, incorporating the analysis of precast segment splicing, temperature shrinkage and secondary force effects. According to the current specifications, dynamic load combinations and seismic loading are implemented, and stress concentration in the negative bending moment area and splicing joints is reviewed. Local thickening, adjustment of steel bars or change of precast segment length can be carried out to achieve structural stiffness and internal force balance.

4.2 Green Construction and Carbon Emission Accounting

In the comparison stage between prefabricated and traditional solutions, the total carbon emissions were calculated using the emission factor method, involving material production, component transportation, on-site construction and hoisting energy consumption, and early operation and maintenance:

$$C_{\text{tot}} = \sum_i Q_i EF_i + \sum_k E_k EF_k \tag{2}$$

In the formula, the amount of material Q_i i (cement, rebar, precast concrete, etc.) used EF_i is the emission coefficient for the manufacturing phase of that material. E_k The consumption of energy and process k, specifically on-site electricity, diesel, and component transportation, is represented by EF_k the corresponding emission coefficient. Considering the line's 26.7-kilometer length and 82% of its bridges, a dual statistical approach based on kilometers and components was employed. For material calculations, Q_i conversions were made using the factory's bill of materials (BOM) and mix ratios, with component weight and actual transportation distance as the benchmarks . E_k During nighttime operations, conversions were E_k made based on actual electricity and fuel consumption. The output, "CO2 emissions per kilometer" and "CO2 emissions per component," provide data support for planning and emission reduction initiatives (such as recycled aggregates, mineral admixtures, and energy efficiency optimization).

4.3 Life Cycle Cost (LCC)

The economic assessment uses a present value model with a 30 to 50 year analysis period as the core tool, using the LCC expression:

$$LCC = C_0 + \sum_{t=1}^{N} \frac{C_t}{(1+r)^t} \tag{3}$$

The formula C_0 defines the investment amount in the initial stage of the project, including design, prefabrication or cast-in-place, equipment installation and renovation expenses. C_t represents the maintenance, functional enhancement, and traffic management costs in year t , r is the social

discount rate, and N is the analysis period. Independent LCCtrad (t) and LCCpref (t) curves are developed for two scenarios, taking into account the social cost factors of prefabricated buildings, such as reduced on-site construction, lowered early maintenance frequency, and shortened traffic closure times during peak hours. By solving LCCtrad (t*), the economic inflection point year t* is identified. Sensitivity tests are conducted on r, material costs, maintenance cycle, and traffic volume penalty factors. Combined with the construction schedule of the 150 -meter main span and nighttime construction, a dual cost accounting system of "components and track kilometers" is proposed to achieve dynamic tracking of maintenance and traffic costs.

4.4 HPFRCC application at the material level

To prevent the spread of cracks in the negative bending and tensile zones of the bridge deck and enhance seismic resistance and fatigue energy dissipation, HPFRCC local reinforcement was carried out on key tension zones and integrated with the prefabricated joint structure. The energy method was used to quantify the toughness of the material:

$$R = \frac{\int_0^{\varepsilon_{\max}} \sigma \mathrm{d}\varepsilon}{\sigma_{\max} \varepsilon_{\max}} \tag{4}$$

Where σ and ε correspond to tensile stress and strain, respectively. The limiting parameters are defined by $\sigma_{\max}$ and $\varepsilon_{\max}$, R which serve as a measure of material toughness. During the construction implementation phase, the length of the reinforced zone is determined based on the distribution of negative bending moments at the 150-meter mid-span. Based on construction ease and deck space limitations, a preliminary selection of the HPFRCC cladding thickness and reinforcement is made (for example, a 30-50 mm cladding at the top edge of the beam, combined with interface roughening and shear stud anchorage). Experimental or numerical analysis is used to verify f_{cr} whether the crack initiation stress and R (ductility ratio) meet the design requirements. The equivalent tension-compression zone stiffness and crack width control parameters are re-substituted into the linear elastic and stage analysis models (version 4.1) to verify whether the deflections and crack limits at the assembly nodes and continuum meet the code and service performance specifications.

5. Effect evaluation

(1) Green construction evaluation

The evaluation system conducts quantitative analysis around five aspects: land, energy, water resources, material use, and environmental impact. Based on the weight and score data in Table 2, the score weight distribution of each dimension is 0.90, 0.76, 0.80, 0.70, and 0.84, with an overall score of approximately 4 points, indicating good overall performance. Figure 2 intuitively maps the relative strengths and weaknesses of each dimension: the edge values of the radar chart correspond to the ideal level of 5.0, and the center benchmark of the radar chart is 0.

Table 2 Green construction expert ratings and weighted scores

Indicator	Weight	Score (1–5)	Weighted Score
Land	0.20	4.5	0.90
Energy	0.20	3.8	0.76
Water	0.20	4.0	0.80
Materials	0.20	3.5	0.70
Environment	0.20	4.2	0.84

Looking at Figure 2, this dimension ranks first, with a weight of 20%. The project has achieved remarkable results in land optimization, comprehensive application of bridges and roads, and integration of old road resources. The environmental score ranks second, with a weight of 20%. This indicator shows that construction noise control, dust suppression and wastewater discharge

treatment have reached a high level. The water quality level is rated at 4.0. After the implementation of rainwater and sewage diversion and recycling water, the water quality is also excellent.

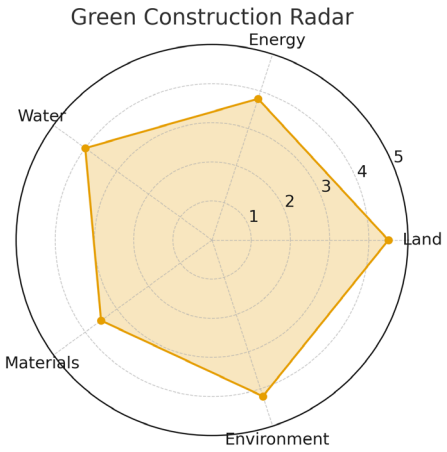

Figure 2 Green Construction Radar

There is a certain gap between the two indicators, Energy (3.8) and Materials (3.5). Energy consumption is mainly limited by the energy consumption of a large amount of temporary lighting and mechanical equipment at night. Taking into account the material composition, some components rely on high-strength steel bars and long-distance transportation, which increases carbon emissions. By improving the efficient management of mechanical loads and enhancing the efficiency of batch transportation of prefabricated components, and incorporating recycled aggregates and mineral mixed additives into the concrete composition, the scores of the two dimensions will increase by approximately 0.3 points each. Equal weights are used in scoring. With this solution, the total score will increase by approximately 0.12 to 0.18 points. This improvement has statistical significance and engineering implementation conditions for the overall improvement of the green construction level.

The smooth edges of the pentagonal outline in Figure 2 confirm the solidity of the project's overall green construction capabilities and accurately reveal the room for improvement in the energy and materials fields. Referring to the aforementioned project characteristics, it is recommended that subsequent efforts be focused on energy management and material substitution to complete the transition from local to overall green performance optimization.

(2) Construction period - transportation - economy

As shown in Table 3, based on the same line length (26.7 km), the adoption of factory prefabrication and on-site rapid assembly reduced the main structure construction time from 300 days to 105 days, a 65% reduction. The Gantt chart shown in Figure 3 further illustrates this time advantage. The upper half of the image utilizes conventional cast-in-place construction, while the lower half utilizes prefabricated construction technology. This clearly illustrates the timing of each key step. Traditional construction methods require the construction of the "substructure" and "superstructure" to be carried out sequentially, creating a long core operation sequence. The prefabricated approach, which utilizes factory prefabrication and nighttime hoisting, enables the simultaneous construction of pile foundations, foundation components, and main structure, significantly reducing the overall construction period.

Table 3 Comparative analysis of construction period, traffic and economy

Metric	Conventional	Prefabricated	Improvement
Project length (km)	26.7	26.7	—
Main structure duration (days)	300	105	−65%
CO_2 intensity (t/km)	1.20	0.85	−29%
Peak traffic closure (days)	180	60	−67%

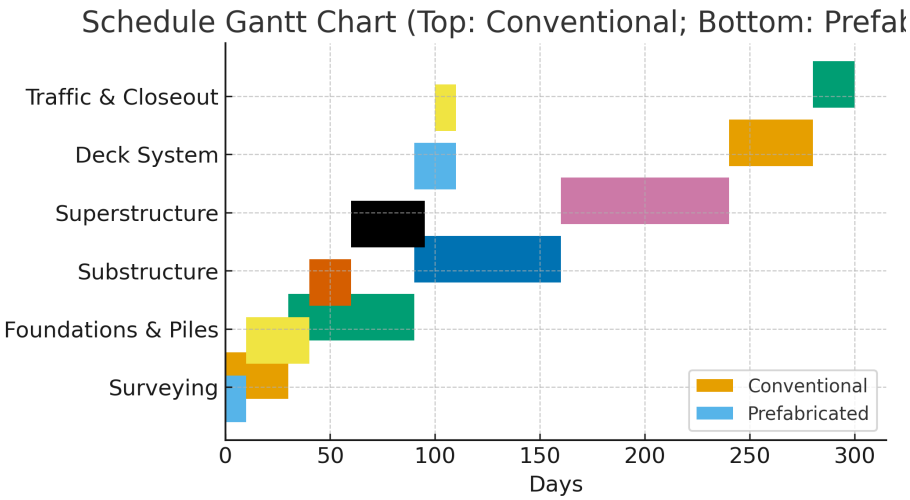

Figure 3 Schedule Gantt Chart

The traffic layout also had a significant effect. The duration of road closures during peak periods was shortened to 60 days, down from 180 days previously, a reduction of more than two-thirds. Figure 3 also confirms the intuitiveness of this result: when traditional methods are used for bridge construction and traffic diversion, roads must be closed for a long time. Relying on rapid splicing and segmented traffic guidance, the prefabricated solution was implemented, significantly reducing the scope and duration of traffic closures. This move significantly reduced the losses directly caused by congestion, and also reduced environmental side effects such as noise and dust caused by construction.

The economic advantage is demonstrated in the LCC curve in Figure 4. The LCC calculation incorporates both the initial investment cost C_0 and subsequent maintenance costs $\sum C_t/(1+r)^t$ calculated at a 5% discount rate . The prefabricated solution offers a slight advantage in initial investment, requires less subsequent maintenance, and incurs lower component replacement costs. The two cost-benefit curves converge between the seventh and ninth years of service. The cumulative cost of the prefabricated solution remains consistently lower than that of the traditional solution. Taking into account the time and socioeconomic losses caused by traffic congestion, this convergence point is expected to occur one to two years earlier.

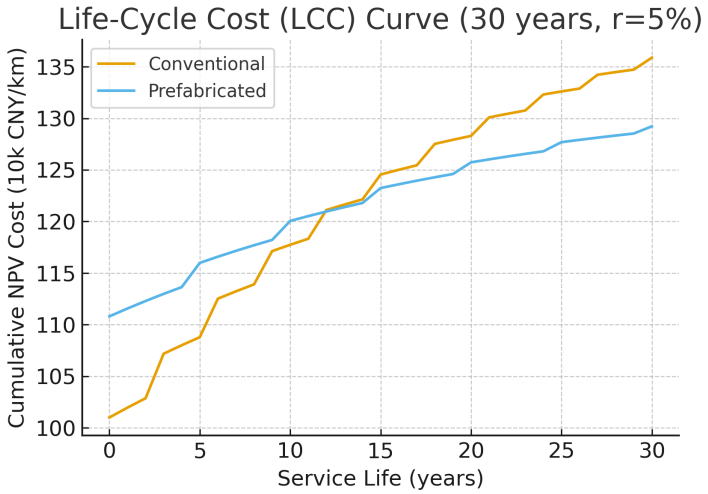

Figure 4 Life-Cycle Cost (LCC) Curve

(3) Material toughness and structural deformation (Table 4; Fig. 2; Fig. 5)

Table 4 provides statistical data on the toughness characteristics and maximum tensile damage of various high-ductility cement-based composites (i.e., SHCC and UHPC) under crack initiation stress. As the stress initiation crack value increases from 2 MPa to 14 MPa, the toughness index

increases from 50% to 83%, showing an increasing trend. The maximum tensile damage decreases from 0.82 to 0.05, clearly revealing the trend of improved ductility and reduced damage.

Table 4 Relationship between crack initiation stress and toughness index of HPFRCC materials

Material	Crack Stress (MPa)	Max Tensile Damage	Resilience (%)
SHCC	2	0.82	50
SHCC	4	0.56	58
SHCC	6	0.30	67
UHPC	8	0.38	67
UHPC	10	0.20	75
UHPC	14	0.05	83

Figure 5 (Comparison of HPFRCC toughness and crack initiation stress) directly shows the nonlinear growth trend of toughness with the increase of crack initiation stress. The first platform area appears near 6 MPa. In the range of 8 to 10 MPa, the performance increases significantly, the initial fracture strength is enhanced, and the self-healing effect of the material to cyclic loads and microcracks is significantly enhanced.

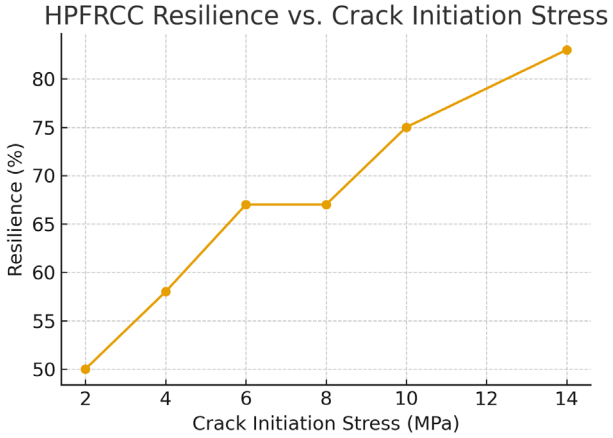

Figure 5 HPFRCC Resilience vs. Crack Initiation Stress

Figure 6 illustrates the structural improvements in the material's performance: the plastic slope of the latter portion of the curve decreases with increasing crack initiation stress. Under the same load, the rate of increase in the structural deflection decreases, the ductility of the component increases, and the residual deformation decreases. Taking the 150-meter-long main span beam of this project as an example, the performance improvement is particularly critical in key tensile areas such as the negative bending moment zone, bridge deck panels, and assembly joints, effectively preventing the early formation and propagation of fatigue cracks.

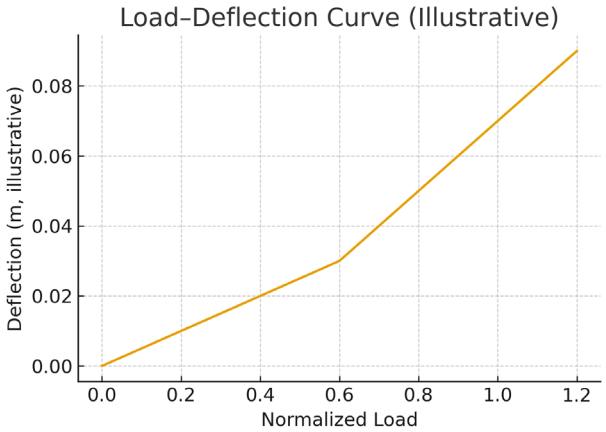

Figure 6 Load–Deflection Curve

Based on previous analysis, it is recommended to add HPFRCC local reinforcement layers to the

negative bending moment areas, assembly nodes and bridge deck tensile areas of key tension members. The implementation measures are explained: During the conceptual design stage, the thickness of the HPFRCC layer was set in the range of 30 to 50 mm, and interface roughening, steel anchorage and shear studs were implemented to enhance the composite effect with ordinary concrete; a combination of factory prefabrication and on-site wet joint casting technology was adopted to ensure that the reinforcement layer and the main structure achieve overall force coordination. By taking this action and adopting this measure, a small amount of material investment can achieve the goals of controlling cracks, extending fatigue life and rapid recovery after earthquakes.

(4) Carbon emission composition and emission reduction priorities

Figure 7 reveals the distribution of carbon emissions throughout the life cycle of prefabricated building solutions: the material manufacturing stage accounts for 55%, the construction and installation part accounts for 20% of the entire process, the component transportation accounts for 10%, and the maintenance and operation part accounts for 12%. At the end of the product life, the disassembly and disposal stage accounts for about 3%. Research data reveals that the material production and processing stage has become the main source of carbon emissions, and the calcination of high-grade cement clinker and the refining of steel bars are the most prominent in carbon emissions.

Achieving low-carbon substitution in the materials field and optimizing energy efficiency at the factory level should be the focus of emission reduction work. By increasing mineral admixtures, using recycled aggregates, and promoting high-content fly ash and low-clinker cement, the carbon emissions of unit strength materials can be reduced. In order to reduce the use of steel bars, it is recommended to give priority to the use of electric arc furnace short-process steelmaking products or high-strength steel bars. Photovoltaic energy utilization, waste heat recovery and automated production should be implemented at the factory end to strive to reduce unit component energy consumption and incidental environmental emissions.

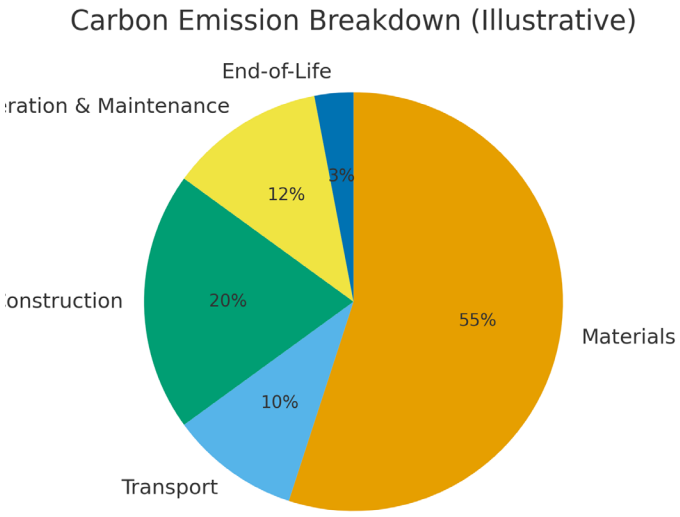

Figure 7 Carbon emissions composition

During the long-term operation and maintenance phase, structural condition monitoring systems and intelligent lighting/ventilation energy-saving measures can be implemented to continuously reduce energy consumption and the number of maintenance operations during the operational phase. At the end of the product life cycle, disassembly design and material recycling and reuse can be adopted to reduce the pressure of end-of-life waste treatment and emissions. The implementation of these comprehensive strategies ensures both structural safety and durability, further reducing the carbon emission intensity of bridge projects throughout their life cycle to below 70%, and simultaneously improving engineering economics and environmental protection levels.

6. Conclusion

This paper analyzes the overall design of municipal bridges in complex construction environments. A comprehensive technical system integrating prefabricated construction, green building, life cycle costing (LCC), and high-performance fiber-reinforced composite materials (HPFRCC) was established and tested. Leveraging standardized prefabrication and a parallel organization mechanism, this solution was implemented, reducing the main construction period from 300 days to 105 days and halving peak-hour traffic closure duration, significantly reducing both construction and social costs. The overall green construction score was approximately 4.0, with top scores in the Land and Environment dimensions. The Energy and Materials dimensions, optimized using high-efficiency equipment and low-carbon mixes, showed potential improvements of 0.12 to 0.18 points. A cost-benefit analysis showed that the cost curves of the two options intersected between 7 and 9 years of service life. Analysis of the value of congestion time suggests that this cost intersection would occur 1 to 2 years earlier. In terms of material performance, with 14 MPa as the crack initiation stress, the toughness index of HPFRCC reaches 83%, and the maximum tensile damage is reduced to 0.05, significantly enhancing fatigue durability and post-earthquake recovery. Accounting analysis shows that carbon emissions from material manufacturing account for 55%, with construction and operation and maintenance ranking second and third respectively. Priority should be given to the implementation of low-clinker cement, recycled aggregates and factory energy efficiency optimization plans.

References

[1] Zheng J, Du H, Mu T, et al. Innovations in design, construction, and management of pingnan third bridge—the largest-span arch bridge in the world[J]. Structural Engineering International, 2022, 32(2): 134-141.

[2] Wei J, Chen G, Huang J, et al. BIM and GIS applications in bridge projects: A critical review[J]. Applied Sciences, 2021, 11(13): 6207.

[3] Li CZ, Guo Z, Su D, et al. The application of advanced information technologies in civil infrastructure construction and maintenance[J]. Sustainability, 2022, 14(13): 7761.

[4] Omrany H, Al-Obaidi KM, Husain A, et al. Digital twins in the construction industry: a comprehensive review of current implementations, enabling technologies, and future directions[J]. Sustainability, 2023, 15(14): 10908.

[5] Yang Z, Tang C, Zhang T, et al. Digital twins in construction: Architecture, applications, trends and challenges[J]. Buildings, 2024, 14(9): 2616.

[6] Choi HW, Kim HJ, Kim SK, et al. An overview of drone applications in the construction industry[J]. Drones, 2023, 7(8): 515.

[7] Kim H, Lamichhane N, Kim C, et al. Innovations in building diagnostics and condition monitoring: A comprehensive review of infrared thermography applications[J]. Buildings, 2023, 13(11): 2829.

[8] Yang Y, Chen Y, Tang Z. Analysis of the safety factors of municipal road undercrossing existing bridge based on fuzzy analytic hierarchy process methods[J]. Transportation research record, 2021, 2675(12): 915-928.

[9] Górecki J, Núñez-Cacho P. Decision-making problems in construction projects executed under the principles of sustainable development—bridge construction case[J]. Applied Sciences, 2022, 12(12): 6132.

[10] Hu W, Lim KYH, Cai Y. Digital twin and industry 4.0 enablers in building and construction: a survey[J]. Buildings, 2022, 12(11): 2004.