Engineering Practice of Promoting Rural Development through the Rapid Application of Prefabricated Bridge Technology in Rural Areas

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ABSTRACT Bridges in rural areas serve as critical nodes within transportation networks, supporting regional connectivity and sustainable rural development. With the rapid advancement of intelligent infrastructure, electromagnetic sensing and wireless monitoring technologies provide important complementary tools for bridge operation and lifecycle management. Prefabricated bridge technology, characterized by factory-based production and on-site assembly, is well aligned with the multifaceted demands of rural bridge construction in terms of efficiency, quality, and cost control. Based on engineering practice cases, this paper systematically elaborates on the concept, characteristics, and advantages of prefabricated bridge technology, analyzes the typical features of rural bridge construction and the technical adaptability of prefabricated solutions, and examines specific projects from the perspectives of scheme design, construction implementation, and performance evaluation. By comparing prefabricated bridges with traditional cast-in -place construction modes, the shortcomings of conventional approaches are identified, and practicable promotion and implementation pathways are proposed. The results indicate that prefabricated bridge technology can significantly shorten construction periods, enhance the stability and consistency of structural quality, and reduce environmental impacts and overall costs. The widespread application of this technology provides strong technical support for upgrading rural transportation infrastructure while offering valuable engineering references for intelligent structural monitoring and electromagnetic sensing-assisted bridge management.

INDEX TERMS prefabricated bridge technology, rural bridge engineering, engineering practice, structural health monitoring, electromagnetic sensing

I. INTRODUCTION

RURAL transportation infrastructure constitutes the fundamental material basis for supporting the bidirectional flow of factors between urban and rural areas, to ensure coordinated regional development and the prosperity of rural residents. Within this system, bridge engineering could serve as critical nodes in rural highway networks and might directly affect integrity and operational efficiency of rural transportation systems. Bridge construction has long been characterized by low construction standards, relatively outdated construction techniques, inadequate structural durability, and shortened service life. However, these deficiencies appear to have gradually become major bottlenecks restricting improvement of rural transportation conditions. Moreover, the significant limitations might additionally restrict effective implementation of the rural revitalization strategy.

The comprehensive advancement of the rural revitalization strategy and acceleration of rural modernization have placed increasing demands on transportation infrastructure in rural areas in terms of industrial development, public services, and residents' mobility. Furthermore, scale expansion and intensification of agricultural production may have generated practical requirements for higher efficiency in agricultural product transportation and improved road carrying capacity. Meanwhile, rapid emergence of new rural economic formats, such as rural e-commerce and rural tourism, has imposed higher standards on accessibility, safety, and operational stability of transportation infrastructure. Thus, rural bridges may be required not only to fulfill basic traffic functions but also to possess enhanced structural safety, extended service life, and strong environmental adaptability. Traditional cast-in-place bridge construction methods, which rely heavily on on-site operations, are associated with long construction periods, significant susceptibility to human and environmental influences, and high dependence on construction sites and skilled labor. Nevertheless, these critical limitations might make them increasingly incompatible with practical conditions of rural areas, which are characterized by short construction windows, complex site conditions, stringent budget constraints, and environmentally sensitive surroundings.

Prefabricated bridge technology demonstrates that industrialized production and modular assembly, whereby the significant structural components of bridges may be standardized and mass-produced in factories and subsequently assembled on site through hoisting and splicing operations, could fundamentally transform construction practice. This construction approach might represent a departure from traditional bridge-building methods that appear highly dependent on on-site casting. Moreover, the approach demonstrates advantages in construction organization, quality control, and environmental protection. Factory-based production may reduce material waste and quality variability while improving component precision. However, on-site assembly reduces the need for scaffolding, formwork, and wet operations. Thus, construction duration shortens and disturbances minimize. Additionally, prefabricated bridge technology shows advantages in reducing dust, noise, and construction waste emissions, which could indicate that the technology may be well aligned with the requirements of green, low-carbon development and ecological protection in rural areas.

As prefabricated construction concepts and technical systems have matured, yielding favorable engineering outcomes. The practical experience suggests that this technology may be suited to small- and medium -span bridge construction. In light of these findings, the technology appears advantageous in rural areas with restricted construction sites, high requirements for traffic organization, and strict schedule constraints. However, application in rural areas remains at an early stage. Nevertheless, systematic investigations into technical adaptability, implementation models, cost-effectiveness, and promotion pathways could be limited and may require further study.

Therefore, a systematic examination of the application logic of prefabricated bridge technology in rural areas, together with an analysis of the compatibility with the characteristics of rural bridge construction, the summarization of technical points and implementation experience from engineering practice, and the formulation of application pathways that might be replicable and scalable, may be of importance for promoting the transformation and upgrading of rural bridge construction models. Moreover, such research could contribute to improving construction quality and efficiency while reducing life-cycle costs and environmental impacts. Thus, research provides support and references for improving rural transportation infrastructure systems. However, research may remove transportation bottlenecks at the "last mile." Additionally, research could stimulate endogenous development momentum in rural regions.

II. OVERVIEW OF PREFABRICATED BRIDGE TECHNOLOGY

A. BASIC CONCEPT AND TECHNICAL CHARACTERISTICS OF PREFABRICATED BRIDGES

Prefabricated bridge technology demonstrates that core structural components—such as girders, piers, abutments, and railings—may be manufactured in specialized factories according to standardized design parameters. Moreover, after these components pass quality inspections, the components are transported to construction sites and assembled into integral bridge structures through hoisting, splicing, and connection operations using lifting equipment [1]. Given that industrialized production enables systematic control, the core characteristics of this technology include industrialized component production, modularized construction processes, and standardized technical application. This approach may effectively overcome limitations of traditional cast-in-place construction dominated by on-site operations and decentralized workflows. In light of factory production capabilities, the significant empirical evidence could indicate that precise concrete proportioning, automated steel reinforcement binding, and steam curing processes might be employed to ensure uniform component quality. Furthermore, compared with on-site casting, dimensional deviation control accuracy of prefabricated components can be improved by more than 40% [2]. However, on-site construction mainly involves hoisting and assembly operations. Thus, construction eliminates large-scale scaffolding and formwork erection.

Nevertheless, the important procedural modifications may suggest that construction procedures are simpli fied and sensitivity to weather conditions and complex terrain is significantly reduced. Additionally, this approach appears particularly suitable for rural areas with limited construction space and variable climatic conditions. Moreover, prefabricated bridge technology might support combinations of standardization and customization. Therefore, component parameters can be flexibly adjusted to meet typical rural bridge span requirements, generally ranging from 5 m to 30 m. Despite varying technical requirements, technology may achieve balance between universality and applicability [3].

B. MAJOR TECHNICAL ADVANTAGES

The advantages of prefabricated bridge technology could indicate systematic superiority over traditional construction methods across four critical dimensions—efficiency, quality, environmental performance, and cost. Moreover, in terms of the significant efficiency dimension, factory-based component production may be carried out in parallel with on-site foundation construction, substantially shortening the construction period. For small- and medium-span bridges, on-site assembly duration is only 50%–60% of that required for cast-inplace construction. Thus, this approach may effectively reduce traffic disruption and adverse impacts on rural production and daily life [4–5].

Given that quality control represents a critical advantage, the controlled factory environment could eliminate common

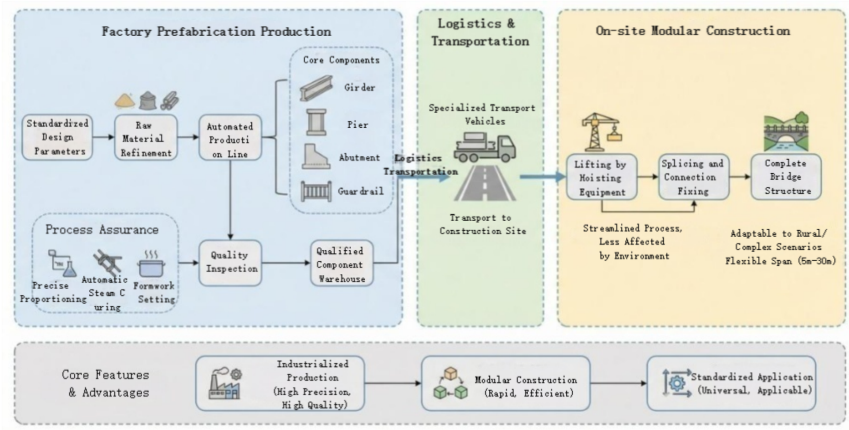

FIGURE 1. Prefabricated bridge technology

defects associated with on-site casting, such as cracking and insufficient strength caused by fluctua tions in temperature and humidity. The strength qualification rate and dimensional accuracy of prefabricated components might be significantly higher than those of cast-in-place components. However, the incidence of quality defects may be reduced by approximately 30%–40% [6–7].

Nevertheless, in terms of the important environmental performance dimension, centralized production might enable precise material batching and cutting, resulting in a reduction of construction waste by more than 80% compared with traditional construction methods. Moreover, on-site hoisting and assembly operations could substantially reduce dust and noise emissions. Therefore, this approach may meet requirements for construction in ecologically sensitive rural areas [8–9].

From a cost perspective, although investments in transportation and lifting equipment can be relatively high when considered for a single isolated bridge project, this case adopted a leasing and regional equipment-sharing strategy, avoiding large one-time capital purchases. Because twelve bridges were constructed in batch within the same county, economies of scale were achieved in both component production and equipment mobilization. Transportation and hoisting expenses accounted for approximately 9% of the total RMB 18 million investment, which remained financially manageable. Therefore, the reported 22% cost reduction resulted from batch standardization, shortened construction duration, reduced formwork expenditure, and lower rework and maintenance costs, rather than from prefabrication alone [10–11].

III. ANALYSIS OF CHARACTERISTICS AND TECHNICAL REQUIREMENTS OF RURAL BRIDGE CONSTRUCTION

A. TYPICAL CHARACTERISTICS OF RURAL BRIDGE ENGINEERING

Rural bridge engineering could demonstrate distinct characteristics influenced by the regional conditions, the significant economic levels, and the critical functional requirements. In terms of span configuration, rural bridges appear to be predominantly small- to medium-span structures. Moreover, most spans may range from 5 m to 20 m. These bridges are mainly used to cross field ditches and rural waterways, with load levels designed to accommodate agricultural vehicles and small passenger vehicles. However, average annual daily traffic volume is generally no more than 400 passenger-car units [12–13].

Construction site conditions are often complex. Given that many bridge sites are located in undulating terrain or ecologically sensitive areas, construction spaces might be limited and transportation access is constrained. Thus, it is difficult for large-scale construction equipment to enter sites. Financial investment is relatively limited. Nevertheless, rural bridge projects primarily rely on special fiscal subsidies and local funding, which may impose stringent requirements on comprehensive cost control while ensuring both economic efficiency and structural durability.

In light of the service environment of rural bridges, conditions are also distinctive. Some bridges must withstand seasonal flooding and water accumulation from agricultural irrigation. Moreover, others are constructed in areas with problematic geological conditions, such as collapsible loess or poorly compacted fill. These factors could place higher demands on impermeability and corrosion resistance of bridge structures [14–15]. Additionally, rural areas often lack skilled construction personnel and specialized construction teams. However, this results in urgent need for construction technologies that are simple in process, easy to operate, and highly adaptable.

B. ADAPTABILITY ANALYSIS BETWEEN PREFABRICATED BRIDGE TECHNOLOGY AND RURAL DEMANDS

The core characteristics of prefabricated bridge technology could indicate that substantial compatibility exists with the demands of rural bridge construction. However, the standardized production of these small- and medium-span components appears well suited to the important dimensional

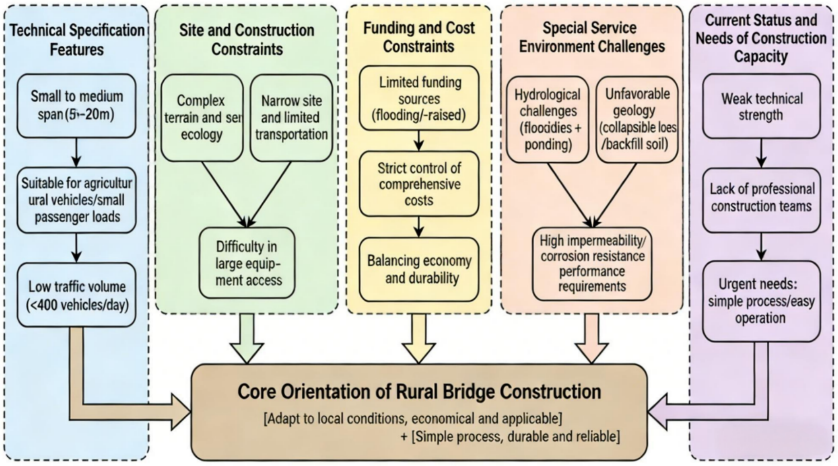

FIGURE 2. Overview of characteristics and construction-oriented requirements of rural bridge engineering

requirements that rural bridges present, and this approach may enable batch manufacturing alongside the repeated use of critical structural components. Moreover, the modular approach might effectively reduce design and production costs. Given that financial constraints commonly present challenges in rural regions, this cost reduction seems significant [16]. The modular construction process may simplify on-site operations. Thus, complex scaffolding systems might be eliminated, and the professional skill level demands on construction teams could be reduced. Nevertheless, this feature appears advantageous in rural areas where technical capacity shows limitations.

Furthermore, the lightweight hoisting operations could demonstrate that narrow construction sites present fewer obstacles, and component installation might be completed using small lifting equipment. In light of these operational advantages, the cost associated with mobilizing large machinery may be reduced, and the difficulty that large equipment presents could be minimized [17]. However, the high strength achieved through factory curing of prefabricated components may enable bridges to withstand complex rural service environments.

Thus, long-term maintenance costs might be reduced, and service life could be extended. The shortened construction period may minimize disruptions to agricultural activities. Additionally, rural traffic disruptions appear less severe than prolonged road occupation can produce, and agricultural production losses that tradi tional construction methods generate might be avoided. Notwithstanding these various technical advantages, the immediate alignment with rural production needs seems particularly relevant to daily life demands.

IV. ENGINEERING PRACTICE OF THE RAPID PROMOTION OF PREFABRICATED BRIDGE TECHNOLOGY IN RURAL AREAS

A. PROJECT OVERVIEW

The case study demonstrate prefabricated construction applied to a rural highway bridge renovation project within a county designated as a rural revitalization demonstration area. Moreover, the project could indicate coverage across three townships and eight administrative villages. Furthermore, construction involved twelve small- and medium-span bridges that adopted prefabricated construction technology. Thus, the project area appears characterized by hilly terrain. Nevertheless, most bridge sites may span irrigation channels and small rivers. Given that certain sites are underlain by collapsible loess, average annual daily traffic volume might range from 200 to 350 passenger-car units. Additionally, certain bridges could require capacity to withstand seasonal flooding that may overtop bridge deck surfaces.

However, the significant project design might adhere to important principles of technical applicability, economic rationality, and environmental sustainability. Moreover, bridge spans could demonstrate standardization at 8 m, 10 m, and 16 m intervals. Furthermore, clear deck width may indicate design matching width of connecting rural road subgrade. Thus, design appears to meet traffic requirements of agricultural and passenger vehicles. Nevertheless, total investment of RMB 18 million and planned construction period of 120 days might suggest the project could shorten construction duration by more than 40 days compared with traditional cast-in-place methods. In light of standardized prefabricated components and modular construction approaches, the critical project achievements may demonstrate simultaneous improvements in the significant construction quality and efficiency, thereby providing the important reliable transportation support for the relevant agricultural material transport and rural tourism development in the surrounding villages.

B. DESIGN OF THE PREFABRICATED BRIDGE TECHNICAL SCHEME

The project adopted prefabricated reinforced concrete T-girders that could serve as the main superstructure, given that rural site conditions and the functional requirements might indicate this approach. Moreover, the structural components included prefabricated circular piers, prefabricated cap-beam abutments, and prefabricated reinforced concrete guardrails, and these critical elements could demonstrate that the overall assembly rate exceeded 85%. Furthermore, the main girders were designed with C50 concrete, and steam curing may have been applied in the factory. Thus, uniform strength development appears evident. However, mechanical connections were used for reinforcement to enhance structural integrity. Nevertheless, reserved splicing interfaces and sealed waterproofing measures were incorporated into the girders to accommodate the humid service environment in rural areas.

Foundation works were designed using prefabricated pile foundations based on site-specific geological conditions. In light of collapsible loess conditions, prefabricated piles were embedded into stable strata to a depth of no less than 2 m, and this approach might improve bearing capacity and resistance to settlement. However, component design followed the Technical Guidelines for the Design and Construction of Rural Highway Bridges. Thus, standardized molds were used to ensure dimensional accuracy and interchangeability. Additionally, pier heights and deck elevations may have been optimized according to hydrological conditions at each site. Given that certain low-water crossings existed, flood control standards could be determined based on the design flood frequency of the roadway subgrade. Moreover, small crawler cranes and loaders were selected as the primary construction equipment to accommodate narrow sites and complex terrain in rural areas. It should be acknowledged that transporting and driving heavy prefabricated piles in areas with collapsible loess and restricted road access presents practical challenges. Compared with cast-in-place bored piles, which offer greater adaptability to irregular terrain and variable soil conditions, prefabricated piles require higher transportation precision and specialized installation equipment. In this project, compact hydraulic pile drivers were used, and temporary road reinforcement measures were implemented to ensure safe delivery and installation. Although construction complexity increased at certain sites, the standardized quality control of prefabricated piles improved bearing capacity consistency. Future projects in remote mountainous areas should conduct comparative feasibility assessments between prefabricated and cast-in-place foundation systems before selection.

C. CONSTRUCTION ORGANIZATION AND IMPLEMENTATION PROCESS

The project may have adopted a parallel operation mode that combined factory prefabrication and the critical on-site assembly, which could demonstrate that this systematic approach was divided into four significant stages: the component production, the transportation to site, the on-site assembly, and the joint treatment. Moreover, component production was undertaken by a qualified professional prefabrication plant, with the components manufactured in batches according to the construction schedule. Furthermore, prior to delivery, each batch underwent strength testing, dimensional deviation inspection, and appearance quality inspection, and only components meeting requirements were transported to site.

However, transportation was carried out using low-bed trailers, with transport routes optimized according to rural road widths. Components were securely bundled and protected to prevent damage during transit. Nevertheless, before on-site assembly, site clearing, foundation excavation, and prefabricated pile installation were completed, followed by foundation curing. Given that hoisting of piers and main girders was conducted concurrently, installation may have followed the sequence of piers first, then girders; middle spans first, then side spans. Thus, total stations were used for precise positioning to ensure installation deviations remained within allowable limits specified by relevant codes.

In light of the girder assembly completion, joint grouting was performed using high-strength grouting materials to fill splicing gaps and enhance overall structural integrity. Additionally, waterproof sealing could have been applied following the guardrail installation. However, throughout construction, a comprehensive quality control system might indicate that monitoring of hoisting accuracy, joint connection strength, and waterproof performance was maintained. Moreover, environmental protection measures were also enforced, with construction waste collected and transported centrally to minimize impacts on surrounding farmland and waterways. Ultimately, the project was completed in 108 days, 12 days ahead of planned schedule.

V. EVALUATION OF THE APPLICATION EFFECTS OF PREFABRICATED BRIDGE TECHNOLOGY

A. ANALYSIS OF CONSTRUCTION PERFORMANCE

Post-construction inspections could indicate that the significant performance indicators met the requirements of the Standard for Quality Inspection and Evaluation of Highway Engineering, demonstrating that these critical construction outcomes may represent substantial effectiveness. Moreover, the average axial deviation of the main girders was 3.2 mm in terms of installation accuracy. The verticality deviation of the piers was controlled within 0.3%, both superior to the allowable limits specified by the standards (axial deviation $\leq$ 10 mm; verticality deviation $\leq$ 0.5%). Nevertheless, load tests may show the bearing capacity of the main girders satisfied design requirements regarding structural performance. In light of the comprehensive quality assessments conducted, inspection records indicated that all sampled batches met the specified concrete strength requirements (100% qualification rate within the tested samples). Minor surface imperfections caused by transportation and hoisting were observed in isolated components and were repaired according to technical specifications. No structural cracking or leakage affecting structural safety was detected during final acceptance inspection. Long-term durability performance will continue to be monitored during operation. However, the actual construction period was 108 days in terms of schedule control. This may represent a reduction of 52 days compared with the estimated 160 days required for traditional cast-in-place construction. Thus, the schedule compression ratio might correspond to 32.5%. Given that rural transportation networks require minimal disruption, this could effectively reduce disruptions to the significant agricultural production and transportation systems.

Additionally, construction efficiency might show significant improvement. The average number of on-site workers required per day was 25, compared with 50 workers under the traditional cast-in-place approach, representing a 50% reduction in on-site labor demand. However, prefabrication involves additional labor input at the manufacturing plant. When total labor input (including factory production personnel and transportation staff) was calculated in cumulative man-days, the overall labor reduction was approximately 18%. Therefore, the primary labor advantage of the prefabricated approach lies in reduced on-site labor intensity and improved productivity rather than a simple halving of total labor input.

TABLE 1. Results of Key Construction Performance Indicators

Indicator	Design Standard	Measured Value	Compliance
Main girder axial deviation (mm)	≤ 10	Average 3.2	Compliant
Pier verticality deviation (%)	≤ 0.5	Average 0.3	Compliant
Concrete strength qualification rate (%)	100	100	Compliant
Schedule compression ratio (%)	–	32.5	–
Reduction in on-site labor (%)	–	50	–
Reduction in total labor input (man-days) (%)	–	18	–

B. ANALYSIS OF ENVIRONMENTAL AND SOCIAL BENEFITS

From an environmental perspective, the important prefabricated bridge technology could substantially demonstrate that construction activities produce significantly reduced impacts on the critical rural ecosystems. Moreover, centralized factory production may indicate increased utilization efficiency of concrete materials by approximately 20% and reinforcement steel by 15%. Thus, total volume of construction waste might show only 18% of that produced under traditional cast-in-place construction. However, this reduced waste volume may significantly reduce pollution risk to farmland and waterways. Given that waste transportation and disposal present environmental hazards, the prefabricated approach could provide important benefits.

Nevertheless, on-site hoisting and assembly operations may eliminate the need for large-scale excavation and extensive temporary support systems. Furthermore, this approach might reduce damage to surrounding vegetation by more than 70%. Notwithstanding these operational changes, the method appears to avoid dust and noise pollution. However, traditional cast-in-place construction may produce adverse effects on daily lives of nearby residents. Thus, the approach could mitigate effects on crop growth.

In light of these developments, the rapid completion of the project could effectively demonstrate that transportation bottlenecks in rural areas were removed. Moreover, average transportation time for agricultural products from surrounding villages may indicate reduction by approximately 40 minutes. Additionally, transportation costs might decrease by 25%. Furthermore, this substantially improved efficiency of agricultural product circulation. Given that bridge capacity and connectivity were enhanced, the development of nearby rural tourism resources appears stimulated.

Within six months after project completion, tourist arrivals in surrounding villages increased by approximately 30% compared with the same period of the previous year. However, this growth cannot be attributed solely to bridge construction. Seasonal tourism trends, local promotional activities, and broader rural revitalization policies may also have contributed. Improved bridge accessibility should therefore be regarded as a facilitating factor rather than the sole causal variable. Nevertheless, the significant standardized construction of bridges could substantially indicate that traffic safety in rural areas improved considerably. Moreover, this improvement may reduce accidents caused by bridge aging and insufficient load capacity. Therefore, travel convenience and safety for rural residents appears enhanced. Additionally, this might strengthen sense of gain from regional development initiatives.

C. COMPARATIVE ANALYSIS WITH TRADITIONAL CAST-IN-PLACE BRIDGE CONSTRUCTION

The prefabricated bridge technology may demonstrate that significant differences exist compared with traditional cast-in-place construction across the critical dimensions of cost, quality, and efficiency. Moreover, the comprehensive comparative analysis presented in Table 2 could indicate these differences based on actual project data. Furthermore, estimated values for the traditional construction approach provide important context.

However, the cost structure might suggest material costs decreased by approximately 15% due to improved utilization efficiency. The prefabricated approach reduced labor costs by 50%. Given that formwork and scaffolding represent significant expenditures, the prefabricated mode decreased these costs by 75%. Never theless, transportation and hoisting costs increased. Thus, the overall project cost may show a reduction of 22% compared with traditional cast-in-place construction.

Moreover, quality stability could indicate the prefabricated approach benefited from standardized factory production. The quality defect rate was only 30% of that associated with traditional construction. In light of these findings, long-term maintenance costs are expected to decrease by approximately 25%–30%. However, efficiency gains might demonstrate the construction duration decreased substantially. Prefabricated construction reduces weather sensitivity for concrete casting and curing processes. However, hoisting operations remain highly sensitive to adverse weather conditions such as strong winds and heavy rainfall. In this project, lifting operations were suspended whenever wind speeds exceeded safety limits specified in relevant construction codes. Therefore, prefabrication improves schedule stability but does not eliminate weather-related risks. Notwithstanding these advantages, the traditional approach shows fewer effective working days by more than 20 days. Therefore, the prefabricated bridge construction may demonstrate comprehensive advantages in rural bridge projects. Additionally, this approach could indicate better alignment with the multifaceted requirements of rural areas for construction quality, efficiency, and cost control.

TABLE 2. Comparative Analysis of Prefabricated and Traditional Cast-in-Place Bridge Construction Modes

Comparison Dimension	Prefabricated Mode	Traditional Cast-in-Place Mode	Difference
Total project cost	RMB 18.00 million	RMB 23.08 million	22% reduction
Construction duration	108 days	160 days	32.5% shorter
Quality defect rate (observed during acceptance inspection)	2.00%	6.70%	70% reduction
Labor demand	25 on-site workers/day + off-site plant/transport labor (included in total man-days)	50 on-site workers/day	50% reduction in on-site labor; ∼18% reduction in total labor input (man-days)
Construction waste generation	8.2 t	45.6 t	82% reduction
Annual maintenance cost	∼RMB 0.09 million	∼RMB 0.12 million	25% reduction

VI. LIMITATIONS OF TRADITIONAL CAST-IN-PLACE BRIDGE CONSTRUCTION TECHNOLOGY

A. PROLONGED CONSTRUCTION DURATION AND INABILITY TO MEET THE DEMAND FOR RAPID RURAL BRIDGE DEVELOPMENT

Traditional cast-in-place bridge construction consists of several sequential steps, such as scaffolding erection, formwork fabrication, reinforcement placement, concrete pouring, curing and formwork removal. These steps are interdependent and cannot be performed in parallel, leading to long construction periods. Due to the complicated meteorological conditions in rural areas, such as frequent rainfall, snowfall and high tempera tures, cast-in-place bridge construction often experiences repeated interruptions, which extend construction periods even further. Therefore, the construction period for small- and medium-span cast-in-place bridges is generally longer than 160 d, which is considerably longer than that of prefabricated construction. Long construction periods prolong the duration of traffic disruption caused by rural bridges, which in turn affects the transportation of agricultural products, the daily travel of local residents and the order of rural production and life. This impact is more significant during the farming season. If construction disruption occurs during this period, the road section under construction will remain occupied for a long time, thus delaying the sales of agricultural products and reducing farmers' incomes.

Long construction periods also increase on-site management costs and safety risks. Because of the clear deadlines for meteorological funding, rural bridge projects must complete construction within a specified time frame. If construction is delayed, the project will face cash flow problems, which will affect the overall construction process and fail to rapidly upgrade the transportation conditions of rural areas.

B. POOR QUALITY CONSISTENCY AND PRONOUNCED DURABILITY RISKS

Traditional cast-in-place construction could demonstrate that the approach relies heavily on these manual onsite operations. In light of the significant evidence from rural areas, professional construction teams appear to be lacking, thus the critical processes may show difficulty in effective control of reinforcement spacing, concrete mix proportions, and compaction during vibration. Construction might be susceptible to human error. Furthermore, on-site casting environments could be influenced by natural factors. However, inadequate control of curing conditions may lead to defects including cracking, honeycombing, and surface voids. These defects might compromise structural strength and impermeability.

Moreover, rural bridges could be exposed to complex service environments, with regions that appear to be characterized by high moisture levels or corrosive soils. Nevertheless, quality defects in cast-in-place components may accelerate structural deterioration. The defects might reduce bridge durability. Given that the evidence suggests significant deterioration patterns, service life could be shortened by approximately 10–15 years compared with design expectations. Thus, inconsistent quality may result in frequent post-construction maintenance. In light of the important findings, repair costs could be elevated. In cases, noticeable damage might occur within 3–5 years after completion. However, repair or strengthening measures may be necessitated. Notwithstanding the observed data, conditions could seriously undermine traffic safety and operational reliability in rural areas. The conditions might fail to satisfy long-term service requirements.

C. SIGNIFICANT ENVIRONMENTAL IMPACTS AND HIGH OVERALL CONSTRUCTION COSTS

In contrast, traditional cast-in-place construction requires extensive scaffolding and temporary support systems, which increase material consumption, labor intensity, and environmental disturbance. A large amount of waste, dust and noise are generated by the cast-in-place construction. Compared with prefabricated construction, the amount of dust discharged from cast-in-place construction is more than 4 times, and the amount of noise is also larger, which greatly disturb the life of residents around the construction site and influence the growth of crops. Rural areas usually have weak ecological environment, and cast-in-place construction may induce soil erosion and river sedimentation because of pollution caused in construction, which destroy the ecological balance and lead to huge cost for post-construction environmental restoration.

In terms of total cost, the material utilization efficiency of cast-in-place construction is low, which lead to waste of concrete, reinforcement steel and other raw materials and increase the cost of materials. A large amount of construction workers are needed, and shortage of labor in rural areas leads to increase of unit labor cost and total labor cost. Formwork and scaffolding are non-reusable investments made once, and longer construction period leads to higher management cost and equipment rental cost. Although no cost need to be invested initially for transportation and hoisting of components in cast-in-place construction, the comprehensive cost of cast-in-place construction is still more than 22% higher than that of prefabricated construction when all factors are considered. In addition, high maintenance cost after construction for a long time lead to huge cost burden in rural areas.

VII. IMPLEMENTATION PATHWAYS FOR PROMOTING PREFABRICATED BRIDGE TECHNOLOGY IN RURAL AREAS

A. REPLACING ON-SITE CASTING WITH INDUSTRIALIZED CONSTRUCTION TO SHORTEN PROJECT DURATION

Regional prefabricated component production bases could indicate that standardized manufacturing for small- to medium-span rural bridges may establish scale-based production systems. Moreover, commonly used components such as the significant structural girders, the critical piers, and the essential guardrails might demonstrate that mass production approaches achieve intensive manufacturing outcomes. Thus, unit production costs may show reduction through these processes. However, a parallel operation mode of “factory prefabrication and on-site foundation construction” might suggest efficiency improvements. Given that component production can proceed simultaneously with site investigation activities, excavation works, and foundation construction, waiting time between the critical construction stages may show substantial reduction. Nevertheless, overall project duration could demonstrate significant shortening.

Transportation schemes may suggest that compact and flexible transport equipment appears suitable for rural road conditions. Furthermore, the planning of efficient transport routes might indicate that component damage and traffic congestion could show prevention during transit operations. However, on-site assembly procedures may demonstrate simplification requirements. Thus, the limited technical capacity of rural construction teams could indicate that standardized assembly manuals and concise technical training programs might provide operational competence improvements. Moreover, hoisting and assembly operations may show efficient execution through these measures. In light of these standardized procedures, the on-site assembly period for small- and medium-span bridges could demonstrate control within 30 days.

B. ENHANCING QUALITY AND DURABILITY THROUGH STANDARDIZATION AND REFINED MANAGEMENT

Local technical standards for prefabricated rural bridges should specify the parameter information of components’ design, production process, quality inspection and assembling. Through the unified specification of component specifications for small- and medium-span bridges, interchangeability and versatility are realized and the uniformity of quality control is enhanced.

Fine-grained management of factory production should be strengthened. Advanced equipments such as automatic reinforcement tying equipment, accurate concrete proportioning system and steam curing should be popularized. Strict control should be exercised on each parameter during the production process and the components in each production batch shall be inspected in full according to strength, dimensional deviation and appearance quality before delivery. The ones that do not meet the requirement shall not be dispatched. Optimization of connection technology should be carried out. High performance grouting materials and sealed waterproof technology for connections shall be adopted to enhance the overall tightness of connections for the girder, pier and abutment components. These measures enhance the bridge's capability against seepage and corrosion, making the structure more suitable to the service environment with humid climate and corrosion influence which are generally seen in rural areas. A whole life cycle quality traceability data base should be established to record the quality information during the production, transportation, assembly and acceptance process of components. Responsibilities at different stages are clarified and the basis for later maintenance is reserved which enhances the service life of the bridge.

C. REDUCING ENVIRONMENTAL IMPACTS AND OVERALL COSTS THROUGH GREEN CONSTRUCTION PRINCIPLES

The implementation of green production concepts may demonstrate significant environmental benefits in prefabrication facilities. Moreover, energy-efficient equipment could indicate that these manufacturing plants might reduce the important energy consumption during production processes. Additionally, the adoption of environmentally friendly processes appears to suggest waste emissions may be minimized. However, construction waste should be collected and recycled. Therefore, resource utilization might improve. Given that on-site operations could affect surrounding ecosystems, compact lifting equipment may minimize the critical vegetation damage and important soil disturbance. Furthermore, the construction approach might indicate that large-scale scaffolding erection could be avoided to reduce these significant ecological impacts. Nevertheless, excavation activities should be limited. Thus, waste materials may require removal. However, proper disposal might prevent pollution.

Moreover, the optimization of cost control strategies could demonstrate that component manufacturing expenses may be reduced through large-scale production methods. In light of prefabricated construction methods reducing labor requirements, these approaches might indicate that important labor expenses could be minimized. Additionally, reusable formwork systems appear to suggest that the significant material consumption costs may be lowered. However, financing mechanisms should be established. Therefore, fiscal subsidies might be secured.

Given that cooperation between local governments and social capital could provide critical financial support, dedicated funding mechanisms may indicate these resources might alleviate the important financial pressure. Furthermore, shortened construction periods could suggest that management costs may be reduced. Thus, capital occupancy expenses might decrease. Nevertheless, overall cost performance appears optimal.

TABLE 3. Implementation Pathways for Promoting Prefabricated Bridge Technology in Rural Areas

Implementation Pathway	Core Objective	Expected Outcomes
Replacing on-site casting with industrialized construction	Shorten construction duration	Total construction period for small- and medium-span bridges controlled within 120 days, more than 30% shorter than cast-in-place construction
Standardization and refined management	Improve quality and durability	100% component qualification rate; bridge service life extended to or beyond design life; post-construction maintenance costs reduced by over 25%
Application of green construction principles	Reduce environmental impact and overall cost	Construction waste reduced by over 80%; overall cost reduced by more than 20% compared with cast-in-place construction; minimized ecological disturbance

VIII. CONCLUSION

Given that prefabricated bridge technology leverages industrialized production and modular assembly, incorporating high-performance composites into these structural components further enhances competitiveness in the efficiency, quality, and environmental performance of rural bridge construction. Moreover, the technology may suggest important compatibility with typical characteristics of rural bridges. These characteristics include small- to medium-span configurations, complex site conditions, limited funding, and insufficient technical capacity. Furthermore, engineering practice might indicate that this technology can shorten construction periods. Additionally, the approach may enhance stability and consistency of construction quality. However, the technology could demonstrate reduced environmental impacts and overall costs. In light of evidence from practical applications, the technology shows benefits beyond improved rural transportation conditions. Nevertheless, the approach may facilitate circulation of agricultural products and could promote development of rural tourism and related industries, thereby providing support for development in rural areas.

Notwithstanding the established role of traditional methods in bridge construction, the inherent shortcomings of cast-in-place construction approaches—particularly in construction duration, quality control, and environmental performance—might indicate that these methods show inadequate capacity to meet practical demands of rural bridge construction. Thus, replacement of traditional construction methods with prefabricated bridge technology may suggest an inevitable trend in upgrading of rural transportation infrastructure. However, establishing regional prefabricated component production bases could demonstrate important pathways forward. Moreover, improved technical standards may indicate significant potential. Additionally, promoted green construction practices might show benefits. Therefore, optimized funding guarantee mechanisms could accelerate application of prefabricated bridge technology in rural areas. As these implementation pathways enhance the supporting role of prefabricated bridges, the integration of functional membranes and reinforced fibers accelerates the transformation of rural transportation infrastructure toward high-efficiency, premium quality, and industrial synergy.

AUTHOR CONTRIBUTIONS

Zihan Ning designed, collected and analyzed the data, and drafted the manuscript. Zihan Ning conducted the study, critically revised the manuscript for important intellectual content, and gave final approval of the version to be published. Zihan Ning participated fully in the work, take public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

CONFLICTS OF INTEREST

The author declares no conflict of interest.

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