Engineering 5 (2019) 1120–1130

Contents lists available at ScienceDirect

Engineering

journal homepage: www.elsevier.com/locate/eng

Research
High Performance Structures: Building Structures and Materials—Review

Thoughts on the Development of Bridge Technology in China

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ARTICLE INFO

Article history:
Received 11 December 2018
Revised 3 January 2019
Accepted 17 January 2019
Available online 4 October 2019

Keywords:
Chinese bridge engineering
Third-generation bridge engineering
Intelligent bridge
Science and technology plan
Construction technology
Management technology
Information technology

ABSTRACT

In the history of bridge engineering, demand has always been the primary driving force for development. Driven by the huge demand for construction since China's reform and opening-up, Chinese bridge has leapt forward both quantitatively and qualitatively in three major stages, by completing the transition from "follower" to "competitor," and finally to "leader." A new future is emerging for Chinese bridge engineering. As an important part of China's transportation infrastructure, the bridge engineering industry is facing challenges in this new era on how to support the construction of a new form of transportation. This paper provides a summary of the status of bridge technology in China, based on a basic analysis of stock demand, incremental demand, and management demand. It is our belief that the Chinese bridge engineering industry must fulfill three outstanding requirements: construction efficiency, management effectiveness, and long-term service. Intelligent technology based on information technology provides a new opportunity for innovation in bridge engineering. As a result, the development path of bridge engineering needs to be changed. This paper puts forward the idea of developing a third-generation bridge project that is characterized by intelligence, and discusses this project's implications, development focus, and plan. In this way, this work provides a direction for the improvement of the core competitiveness of China's bridge engineering industry.

1. Introduction

Bridges overcome geopolitical barriers by providing a medium for the extension of the human reach. They have become important channels in the expansion of living space for humans, and thus greatly promote social development. The functional, social, and cultural values of bridge engineering are closely related to the political, economic, and cultural activities of human society. These values transcend the bridge itself, transforming it into an infrastructure possessing both social and cultural attributes. Modern bridges have become the epitome of social development and are an important social asset.

The four decades since China's reform and opening-up were a golden period for the development of bridge construction in China. Following the general laws of technological development and the path of integration–development–innovation, Chinese bridge engineering has undergone three stages: learning and following in the 1980s, tracking and improving in the 1990s, and innovating and transcending since the start of the 21st century. The development of bridge engineering in China has now taken a substantial leap forward [1], with the construction of many extra-large bridges adopting novel structures, difficult designs and construction, and complicated hi-tech materials and procedures; examples include the Su Tong Yangtze River Highway Bridge, Tianxingzhou Bridge, and Lupu Bridge. Furthermore, China actively participates in and hosts international competitions, and has played a role in the construction of many well-known international bridges, including the Malaysia Penang Second Bridge, the Panama Canal Third Bridge, and the New Oakland Bay Bridge. These projects have won China 34 outstanding international awards such as the International Federation of Consulting Engineers (FIDIC) excellence award for "Major Civil Engineering Project of the Last 100 Years," the "Outstanding Civil Engineering Achievement" award issued by the American Society of Civil Engineers (ASCE), and the "Outstanding Structural Engineering Award" issued by the International Association for Bridge and Structural Engineering (IABSE). These awards mark the development of the Chinese bridge industry

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https://doi.org/10.1016/j.eng.2019.10.001
2095-8099/

and represent the respect and recognition of the international bridge industry. Chinese bridge engineering has gradually moved into the center of the world stage [2–5].

However, the internal and external environment that has been developing in recent years has brought the Chinese bridge industry to a new starting point, which new requirements for the development of bridge engineering are aimed at. The Chinese bridge engineering industry has been confronted with major questions in this new era regarding how to support the construction of "transportation power." These questions include: How can bridge engineering support China's major national strategies? How can bridge safety be ensured? How can the dream of making China into one of the world's foremost bridge engineering countries be realized? Faced with these new historic tasks, we must rely on the status quo of Chinese bridge engineering technology, examine the direction Chinese bridge technology is moving in with a broader vision, seize current opportunities for further development, and promote Chinese bridge engineering using a rational and scientific approach.

2. The current situation of bridge technology in China

China's reform and opening-up, along with the accompanying economic development, has brought unprecedented opportunities for the development of bridge engineering in China, resulting in a continually increasing scale of bridge construction. More than 830 000 bridges were built in China by the end of 2017. China is recognized for its bridge engineering due to a number of world-renowned bridge projects that have had significant international impact. China's bridges account for more than half of the world's top 10 bridges under each category (Table 1). The brilliant achievements of the Chinese bridge industry have been widely recognized by society. Bridges have become one of the most important brands in China's infrastructure construction, and international recognition of Chinese bridges is continually increasing.

These achievements are due to the considerable amount of scientific and technological research that has been carried out by the bridge engineering industry in China, based on its own needs. This industry has made great progress in four aspects: material technology, survey and design technology, construction technology, and management and maintenance technology.

2.1. Key technical achievements

2.1.1. Material technology

Materials are the basis of bridge engineering; thus, the development of extra-long bridges has been based on the development of material technology. Thus far, China has achieved the domestic production of concrete, steel, cable, composite materials, and intelligent materials. Some of these materials represent world-leading technologies [6–8].

C50 and C60 concretes are widely used in China. Fiber, lightweight, and ultra-high-performance concretes have also been studied and are gradually being applied. A great deal of attention has been paid to improving the performance of concrete materials to improve their structural performance.

The development of steel in China has passed through the stages of low carbon, low alloy, high strength, and high performance. At present, Q345 and Q370 steels are widely used, and Q420 is gradually being applied. Q500 steel has been successfully developed and applied to the Shanghai–Nantong Yangtze River Bridge and other projects. 700 MPa-grade steel is currently under

Table 1
Top 10 bridges of various types.

Bridge name	Main span (m)	Country	Date of construction
Cable-stayed bridge			
Russky Island Bridge	1104	Russia	2012
Shanghai–Nantong Yangtze River Bridge	1092	China	Under construction
Su Tong Yangtze River Highway Bridge	1088	China	2008
Stonecutters Bridge	1018	China	2009
Wuhan Qingshan Yangtze River Bridge	938	China	Under construction
Edong Yangtze River Bridge	926	China	2010
Jiayu Yangtze River Highway Bridge	920	China	Under construction
Tatara Bridge	890	Japan	1999
Normandy Bridge	856	France	1995
Chizhou Yangtze River Bridge	828	China	2019
Suspension bridge			
Akashi Kaikyo Bridge	1991	Japan	1998
Liuheng Link Shuangyumen Bridge	1756	China	Under construction
Yangsigang Yangtze River Bridge	1700	China	Under construction
Humen Second Bridge Nizhou Waterway Bridge	1688	China	2019
Shenzhong Link Linding Sea Bridge	1666	China	Under construction
Xihoumen Bridge	1650	China	2009
Great Belt Bridge	1624	Denmark	1998
Izmit Bridge	1550	Turkey	2016
Gwangyang Bridge	1545	Korea	2012
Runyang Bridge	1490	China	2005
Arch bridge			
Chaotianmen Yangtze River Bridge	552	China	2009
Lupu Bridge	550	China	2003
Hejiang Yangtze River Bridge	530	China	2013
Zigui Yangtze River Bridge	519	China	Under construction
New River Gorge Bridge	518	America	1977
Bayonne Bridge	504	America	1931
Sydney Harbour Bridge	503	Australia	1932
Wushan Yangtze River Bridge	492	China	2004
Chenab Bridge	480	India	2010
Mingzhou Bridge	450	China	2011
Girder bridge			
Shibanpo Yangtze River Bridge	330	China	2006
Stolmasundet Bridge	301	Norway	1998
Raftsundet Bridge	298	Norway	1998
The First Beipan River Bridge	290	China	2013
Sandsfjord Bridge	290	Norway	2015
Paraguay River Bridge	270	Paraguay	1979
Humen Bridge Auxiliary Channel Bridge	270	China	1997
Su Tong Bridge Auxiliary Channel Bridge	268	China	2008
Red River Bridge	265	China	2002
Ningde Xiabaishi Bridge	260	China	2003
Sea-crossing long bridge			
Hong Kong–Zhuhai–Macao Bridge	50	China	2018
Hangzhou Bay Bridge	36	China	2008
Jiaozhou Bay Bridge	35.4	China	2011
East China Sea Bridge	32.5	China	2005
King Fahd Causeway	25	Bahrain	1986
Zhoushan Continental Island Project	25	China	2009
Shenzhen–Zhongshan Bridge	24	China	Under construction
Chesapeake Bay Bridge	19.7	America	1964
Great Belt Bridge	17.5	Denmark	1997
Oresund Bridge	16	Denmark	2000

development, and epoxy-coated steel bars and stainless steel bars are gradually being applied.

In terms of cable materials, 1770 MPa steel wire and 1860 MPa steel strands have been localized and applied in engineering. 2000 MPa steel wire (a zinc aluminum alloy) has also been successfully developed and applied.

Composite materials, such as fiber-reinforced plastic (FRP), have been applied in bridge repair and reinforcement, and corresponding application research on cables has also been carried out. New intelligent materials such as memory alloys, piezoelectric materials, optical fibers, and intelligent self-repairing concrete have gradually been researched and applied in bridge monitoring and reinforcement engineering.

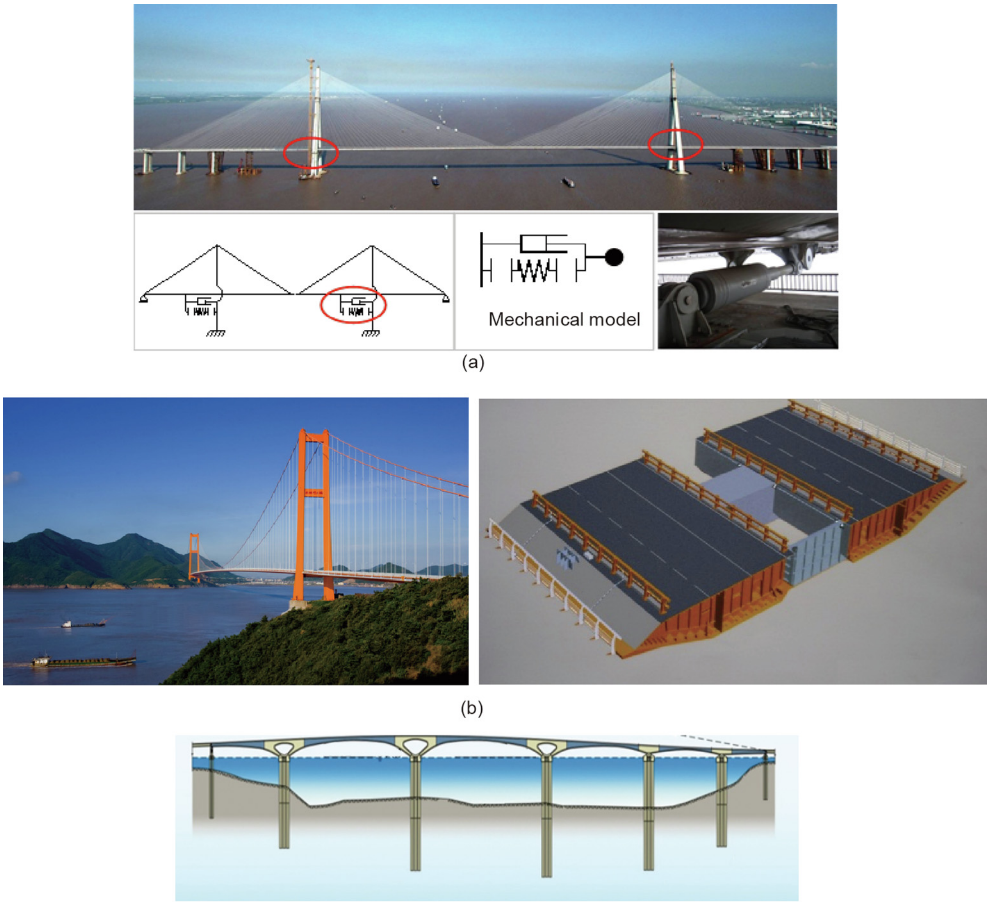
2.1.2. Survey and design technology

Survey and design technology is a prerequisite for the development of bridge engineering. China comprises a vast territory with various geological and topographic conditions; this has promoted diversified development of bridge types and led to the development of survey and design technology. Thus, bridge engineering in China has progressed greatly in terms of survey technology, design theory and methods, bridge type and structural system, key structures, disaster prevention and mitigation technologies, and bridge information technology.

For surveying, modern spatial-information technologies such as remote sensing, global positioning systems, geographic information systems, and so forth, can be used to obtain geological interpretation maps, orthophoto maps, digital elevation models (DEMs), point cloud data, and more. Great progress has been achieved in surveying using drone-based photographing technology, which provides accurate geological interpretation data for design, support for the accurate calculation of earthwork volume and engineering quantity, and a basic data platform for intelligent line selection and three-dimensional (3D) design.

Similarly, design theories have gradually improved, developing from the allowable stress method to the performance-based design method. The decision-making method has become more reliable, as it has shifted from being solely based on experience, to being based on a combination of probability and experience. A decision-making method has now been established that integrates experience, probability, and risk assessment. The design concept has gradually been improved, and has shifted from reliability design to life-cycle design. Moreover, sustainable design, which is based on the concept of sustainable development, is now in its infancy. Advances in design theory and methods have greatly promoted international recognition of China's bridge technology [9–11].

In terms of bridge type and structural systems, Chinese engineers have mastered all kinds of bridge design techniques and have continuously innovated and developed structural systems and key structures. Based on the four bridge types (girder bridges, arch bridges, cable-stayed bridges, and suspension bridges), technologies suitable for local conditions have been developed. These include innovative bridge types such as the structural system of a cable-stayed bridge [12] with a static limit and dynamic damping, the split steel box girder suspension bridge, the hollow continuous steel bridge, and the concrete-filled steel tube arch bridge (Fig. 1). Based on these achievements, new bridge types such as



(a)

(b)

(c)

Fig. 1. Innovative bridge types. (a) Static limited dynamic damping structure system (Su Tong Yangtze River Highway Bridge); (b) split steel box girder suspension (Xihoumen Bridge); (c) rigid-frame bridge (China–Maldives Friendship Bridge).

low-rise cable-stayed bridges, cable-stayed-tie-arch bridges, and cable-stayed-suspended cable bridges have been developed. Together, these achievements form a modern system of bridge types and structures that takes the girder bridge, arch bridge, cable-stayed bridge, and suspension bridge as its main body.

The key structural elements of a bridge—such as bridge towers, main girders, cables, arch ribs, and foundations—are constantly being developed and innovated [13,14]. The design technologies of structures such as concrete bridge towers, steel towers, and steel–concrete composite bridge towers over 300 m have been learned, and new anchorage structures such as the built-in steel anchor box and the plan looping cable have been put forward. Innovations and breakthroughs have been achieved for the structural forms of the main girders: The split steel box girder has been successfully applied to a suspension bridge for the first time, and a three-main-truss steel truss girder is under development. Furthermore, the design technologies for steel–concrete composite girders and hybrid girders are becoming more mature. The strength, life, and intelligence of the cable and anchorage system have been steadily improved, with the development of a high-strength durable parallel wire stay-cable system with a designed service life of 50 years, a distribution-force anchorage system, and a real-time monitoring unbonded replaceable pre-stressed anchorage system for the main cable of the suspension bridge. Concrete arch ribs, steel box arch ribs, steel truss arch ribs, and steel tubes and rigid skeleton composite arch ribs are widely used, and have led to the achievement of world records for the spans of various arch bridges. For substructures, key design technologies for new types of foundations have been developed, including: the super-large group pile foundation, with an abnormal shape and a variable cross-section dumbbell shaped cap; the super-large diameter bored pile foundation; the large steel–concrete composite caisson foundation; the large circular underground continuous-wall anchorage foundation enclosure; the caisson and pipe column composite foundation; and the infinity-type underground diaphragm wall foundation.

Theoretical methods, experiments, and control techniques have been developed in order to address disaster prevention and reduction. Proposed methods include: the state-space method and full modal-analysis method for the 3D vibration analysis of bridges; the buffeting analysis method for the action of oblique wind; a method based on the probability evaluation of wind vibration [15]; bridge seismic design theory [16], which is based on the life-cycle and performance of a bridge; the virtual excitation method for multi-point stationary/non-stationary random seismic analysis; and the performance-based bridge-collision design method. Numerical wave flow pool simulation technology and independent intellectual property analysis software [17] have been developed; these methods have been used to form a preliminary bridge disaster-prevention-and-reduction technology system that covered wind, earthquakes, ship collision, wave flow, and vehicles, which ensured the realization of bridge functions and bridge safety. At present, research into China's bridge disaster-prevention-and-reduction technology is developing from a focus on single-factor disasters to one on the coupling of multiple disasters.

In the field of bridge information technology, significant progress has been made in the development and application of bridge software, with the main functions, calculation accuracy, and calculation and analysis efficiency approaching the level of foreign software (Table 2) [18]. As an effective means of improving a bridge's level of informatization, building information modeling (BIM) technology has been highly valued at all levels in China, and has been applied to the bridge forward design, collision inspection, construction process simulation, and construction progress management of pilot projects; it has also been applied to scheme optimization and selection, in combination with virtual reality/augmented reality (VR/AR) technology. Breakthroughs have been made in integrated modeling and analysis technology, and in the construction of management platforms based on BIM.

Table 2

Computer-aided design (CAD) and bridge analysis software developed in China.

Type	Typical software	Features
Design analysis and construction control	QJX, GQJS, PRBP, BINAS, Dr. Bridge	Functions: mainly for tie bar elements; structures' overall calculation, analysis, checking calculation, and construction control, etc. Accuracy and efficiency: compared with foreign software, the error is within 2%, and the efficiency of calculation and analysis is similar Application: widely used in China
Analysis of bridge spatial effects	There is no market-recognized special software	Function: spatial stress analysis, crack analysis, fatigue analysis, etc. of key components Application: other general finite-element software used in foreign countries, such as Ansys, Abaqus
CAD-aided design	Bridge Designer, BridgeMaster	Function: rapid drawing of two-dimensional (2D) design drawings of skew curve bridges, interchanges, conventional medium and small bridges, etc. Application: good compatibility with domestic norms and a high degree integration with actual projects; substantial market share in China
Professional disaster prevention and reduction	Numerical Wind Tunnel	Function: reference including research achievement, advanced in terms of theory Application: wind resistance, earthquake resistance, ship collision prevention, etc. for bridges

2.1.3. Construction technology

China possesses the construction and control technologies for various types of bridges under different construction conditions, and the industrial technologies for construction are developing rapidly, with constant improvement in terms of the automation level, production efficiency, and quality stability. The majority of the main construction equipment used in bridge construction is made in China. The automation level and equipment-production capability have also improved significantly [19–22].

In terms of construction technology and equipment for super-high bridge towers, developments include: hydraulic climbing formwork technology for concrete bridge towers; super-high concrete pumping technology; construction technology for prefabrication and hoisting; and high-precision assembly for steel bridge towers. Internationally advanced levels have been reached in the maximum length of the casting section of the concrete bridge tower (6 m per section, for a section height of 6 m), the construction efficiency of the climbing formwork (12 d per section), the tower top inclination error ($\leq 1/42\,000$) and the lifting speed under the maximum lifting weight ($7.5\ \mathrm{m{\cdot}min^{-1}}$) for a steel bridge tower. A 5200 t tower crane has been independently developed and used in actual projects.

In terms of the construction technology and equipment of the main girder, developments include: digitalized manufacturing production lines for steel box girders; pre-casting and erection technology for monolithic concrete girders; girder conveyance and erection on constructed girders; pre-casting and assembling construction technology using the short-matching method; construction technology for lifting a steel box girder as a whole; major girder erection and construction technologies with a riding-cable crane; the bridge deck crane; and incremental launching and sliding formwork. Key equipment such as the floating crane, bridge-erecting machine, bridge deck crane, riding-cable crane, large gantry crane, and sliding formwork equipment have been developed independently. The lifting capacity of the riding-cable crane (900 t) and its rotating construction technology (a rotating body length of 198 m and a rotating body weight of 22 400 t) are at an internationally advanced level.

In terms of cable manufacturing and installation technologies and equipment, developments include hot-extruded polyethylene protective cable technology for cable-stayed bridges, and the formation technology of a hot-extruded cable sheath. Super-long stay cable erection technology with a soft-hard combination and three-stage hauling has been developed and is widely used in cable-stayed bridges and arch bridges. Main-cable installation technology using the prefabricated parallel wire strand (PPWS) method has been learned.

In terms of construction technology and equipment for arch ribs, developments include: construction technologies such as cable-stayed suspension and connection with cantilever assembling and cantilever casting; stiffening technologies for rib skeletons; reinforced concrete arch bridge rotation; and lifting technologies for large sections of steel arch bridges. For example, the main span of the Beipanjiang Bridge on the Shanghai–Kunming railway that was built using the stiffening skeleton construction method is 445 m long, which is far longer than bridge spans in foreign countries (the greatest of which is 210 m) [23]. The three-stage continuous vacuum-assisted pumping method has been adopted in the stiffening skeleton-encased concrete casting technology in order to improve the conveyance efficiency to 30.8 $m^3 \cdot h^{-1}$. The main span of Chaotianmen Bridge, which was built using the technology of cantilever-assembling erection through cable-stayed suspension, is 552 m. Using the construction method of arch rib rotating, the maximum lifting tonnage by the horizontal rotation method is 17 300 t, and a vertical rotation method has also been developed. The maximum lifting weight by the large-section lifting method is 2800 t. Construction equipment such as the large-tonnage cable crane (with a maximum lifting weight of 420 t and a height of 202 m) has been developed. Furthermore, the arch rib construction technique is becoming increasingly common in the industry.

In terms of construction technology and equipment for bridge foundations, developments include the large-diameter bored pile, large-diameter steel pipe pile, pre-stressed high-strength concrete (PHC) pipe pile, steel pipe composite pile, large-pile group foundation, large caisson foundation, and super-deep underground continuous wall foundation. Bridge construction equipment such as the pile-driving ship, hydraulic piling hammer, drilling machine, concrete mixing ship, and double-slot milling machine have been developed independently. The capacity of the pile-driving ship (ϕ7 m, pile length over 100 m, weight of 600 t) has exceeded that of similar ships in foreign countries (e.g., ϕ2.5 m, pile length of 80 m, weight of 100 t) [24].

In terms of bridge erection technologies, industrial construction technologies are developing rapidly, and the automation level is constantly improving. For the erection of structural elements, integrated driving of the precast pile foundation, preassembly of the cap and pier body, and integral lifting of the prefabricated steel bridge tower have been achieved. For the main girder, large-scale pre-casting and erection technology has been realized for all operations, including the prefabrication and assembling of small sections of concrete box girders, prefabrication and lifting of big sections of truss girder, integral erection of super-large sections of the steel box girder over waterways, and erection of the precast concrete main girder by means of a bridging machine. Automated erection has been applied from the upper structure to the substructure. Furthermore, technology promoting the rapid repair and replacement of large bridge sections has been developed for upgrading old bridges, in order to minimize the interference of construction on busy traffic.

In terms of construction control technology, the unstressed state control method for staged forming [25] has been developed to solve the segmental construction of bridges, based on the conventional double control of deformation—internal force, and combining with the geometric control method proposed by the concept of unstressed state control. Besides, a geometric control method has been proposed for the entire process of the design, manufacture, and unstressed member installation. This has greatly improved the construction control accuracy of long-span cable-stayed bridges. A construction control system that integrates functions such as calculation, analysis, data collection, instruction emitting, error judgment, and more is currently under development. Intelligent and information-based construction control technology for bridges based on networks is becoming the focus of research in this field.

2.1.4. Management and maintenance technology

With the rapid development of bridge construction, great progress has been made in bridge management and maintenance, monitoring, inspection, and evaluation technologies in China [26,27].

Regarding management and maintenance, a two-level method that focuses on preventive maintenance supplemented by corrective maintenance has been established.

In the field of monitoring technologies, a series of sensors and monitoring products—such as a centimeter-level real-time dynamic differential global positioning system, and a full series fiber grating meter—are being widely used. A series of signal-acquisition devices, such as a microsecond clock synchronous vibration signal conditioner and a 100 Hz high-speed scanning fiber demodulator, have been studied and developed. Monitoring technologies based on a dual-ring redundant fiber ring network and on industrial Ethernet have been created, and structural safety monitoring systems have been equipped on hundreds of bridges. The system-integration technology is becoming increasingly mature.

With regard to inspection, technologies such as bridge concrete nondestructive testing, fatigue crack detection in steel structures, underwater pile-foundation detection, damage identification using high-definition cameras, bridge static-load testing, and a series of testing equipment such as a cable-inspection robot and a bridge-inspection car have been developed. Testing equipment is becoming more and more specialized and intelligent, and the focus of testing technologies has shifted from destructive testing to nondestructive testing.

In terms of evaluation technologies, an evaluation method has been proposed to determine the technical condition of a bridge that combines layered and comprehensive evaluations with five single-control indicators of the bridge; the evaluation indicators have also been refined. An evaluation method has been put forward that is based on the test results of bridges and the bearing capacity from structure-checking calculations, and a comprehensive evaluation method based on evaluations of the bridge-bearing capacity, durability, and applicability has been proposed. The reliability and comprehensiveness of the evaluation results have also been improved.

With regard to reinforcement technology, new methods and processes—such as carbon fiber composite materials and external pre-stressing reinforcement—have been applied to bridge maintenance and reinforcement. Cable (hanger) replacement technologies and main girder replacement and reinforcement technologies are developing rapidly. New coating and joint-protection technologies for cathodic protection have been studied and developed independently. A thorough bridge maintenance, repair, and reinforcement technological system has been established that shifts the focus from passive to active protection.

In terms of information management and maintenance, an informatized decision-making support system for the management of bridge assets and maintenance has been established. Using just one ID code, various construction documents, monitoring equipment, monitoring data, maintenance data, and other pieces of information in the process of bridge construction and management can be managed and utilized to assist decision-making, in order to ensure the uniqueness, visualization, automation, and controllability of information management.

2.2. Existing problems

China has made brilliant achievements in bridge engineering in the 40 years since the country's reform and opening-up. However, in comparison with developed countries, problems and shortcomings remain in four key fields. Breakthroughs are still needed in certain basic theory areas and common key technologies. Moreover, construction is insufficiently refined; the level of industrialization, information, and intelligence is insufficiently high; the innovation and research conversion capacity is insufficient; and the industrialization level is somewhat low. These restrictions affect the long-term development of China's bridge industry, and are summarized below [4,28]:

(1) **Material technology.** China is still catching up with Western countries in terms of research and development and the application of advanced materials. Research on high-performance concrete remains at an elementary stage (i.e., imitating the work of others), and the mechanical performance indicators are lower than those of foreign high-performance steel. In comparison with Western countries, large gaps exist in terms of steel weldability, strength, plate thickness, and weatherability. Furthermore, high-performance and large FRP- and shape-memory alloy (SMA)-based products are still being imported.

(2) **Survey and design.** China falls behind Western countries when it comes to research and application of basic theories, perspective study, intelligent technology, and independent intellectual property software.

(3) **Construction.** The industrialization of construction technologies remains rudimentary, and the performance and reliability of the construction equipment are in urgent need of improvement. Intelligent construction technology and equipment also need to be developed. The stability of the construction quality also needs improvement urgently.

(4) **Maintenance and management.** The following areas in maintenance and management remain relatively underdeveloped: monitoring and testing technologies and equipment; the theory and method of structural state evaluation; maintenance, repair, and reinforcement technologies; and the development of intelligent technology.

Above all, bridge engineers still face the reality of lacking core technologies and equipment in terms of design, manufacturing, construction, management, and maintenance. This lack restricts further development of bridge engineering in China, and poses risks to China's competitiveness in this industry. At present, in addition to acknowledging the current gap in key technologies, we should be aware of a series of deep-rooted problems that exist in the construction of the innovation system, concept leading, mechanism construction, and technology application in China, as follows:

(1) **Innovation system.** There are two weaknesses in the construction of the innovation system: insufficient capacity building and insufficient strategic leadership. The strength of existing bridge construction and maintenance technologies is not enough to support China in moving forward into the ranks of world-leading bridge manufacturing.

(2) **Concept leading**. A determined will for scientific research and a down-to-earth attitude are both lacking in China. There are two extremes: either avoiding innovation entirely, in order to avoid risk, or innovating purely for the sake of innovation.

(3) **Mechanism construction.** Two problems hinder the establishment of an innovation mechanism in China: the homogenization of innovation platforms and the repeatability of research. The sharing of scientific achievements is very lacking, and there is a serious waste of scientific research resources.

(4) **Technology application.** Two shortcomings affect the application of innovative technologies: The degree of refinement is not high and the scale level is insufficient. The level of industrial transformation of new technologies is low, which makes it difficult for the developers to profit and restricts continuous development.

The deep-rooted problems described above create an unsuitable environment for the development of core technologies in bridge engineering, which will further aggravate the current problem of a lack of core technologies. Therefore, we must continue to study the characteristics of bridge construction, seize opportunities for a new round of industrial revolution and development, implement long-term strategic plans for scientific and technological breakthroughs, innovate the system and mechanism, and fundamentally improve our innovation and development ability in bridge construction.

3. Opportunities and challenges in the development of bridge engineering

History shows that demand is the first impetus for the development of bridge engineering. In recent years, changes in internal and external demands, which include the introduction of new demands, have positioned the development of China's bridge engineering at a new starting point.

The first change is in incremental demand. With the proposal of national development strategies such as the Belt and Road Initiative, the Yangtze River economic zone, and the coordinated Beijing–Tianjin–Hebei development, the demand for bridge construction remains exuberant. In future, however, bridge construction will gradually expand to important cross-sea channels in China and Eurasia, and to remote mountain valleys; this shift will result in more complicated construction conditions, larger bridge spans, and larger structure scale. Moreover, it is necessary to shift viewpoints from considering single disasters to considering multiple disasters. Quality security, economic durability, environmental protection, and energy conservation will be emphasized more, and higher service life and better performance are desirable. Many new problems and technologies will demand prompt solutions.

The second change is in stock demand. By the end of 2017, the total number of highway bridges in China reached 0.8325 million, ranking first in the world. With the current 3% annual growth rate of bridges in China, this number is expected to exceed 1 million in 2025. At the same time, due to the aging of bridges and the deterioration of service conditions, many bridge-disease problems are arising, and security-related accidents are increasing in number. At present, the total number of bridges that are considered "dangerous" in China is about 70 000 (Fig. 2), accounting for a twelfth of existing bridges in China, and this proportion will continue to remain at a relatively high level. The heavy-maintenance tasks required to repair aging Chinese bridges have placed new demands on bridge maintenance technology.

The third change is in management needs. Chinese social development is shifting from high-speed development to high-quality

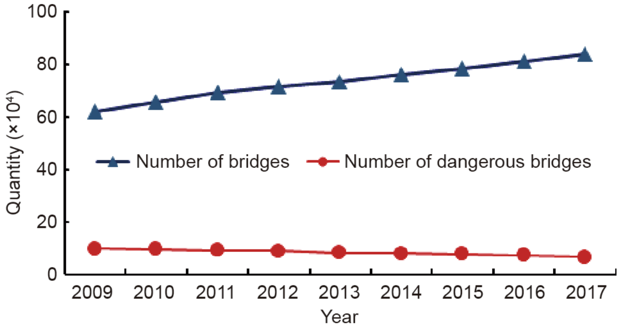


Fig. 2. Recent developments in the total number of all bridges (blue) and total number of "dangerous" bridges (red) in China.

development. As a result, the main concept behind the development of bridge engineering has changed from "can be built" to "can be built and managed well," which places higher requirements on the quality of construction and management. At this time, the development of bridge engineering must be guided by the concepts of quality reform, efficiency reform, and motivation reform, and the building efficiency and engineering quality of Chinese bridges must be improved through technological innovation.

In general, China's bridge engineering industry must address domestic demands for construction technology, maintenance technology, and scientific decision-making in future; it will also encounter the management needs of quality improvement, rapid establishment, and innovation. The question of how to build efficiently, manage effectively, and serve over the long-term encapsulates the three major challenges of bridge development in China today. For the long-term survival and healthy development of the bridge industry, it is imperative that a reform be carried out that covers its entire industrial chain.

At present, a new round of technological revolution and industrial transformation is on the rise, and global technological innovation presents a newly developing trend of intelligence and information. The new generation of information technology is changing how humans live, and has brought revolutionary changes to traditional industries. Bridge construction and maintenance technology is an important carrier for the development of industry including materials, equipment manufacturing, information, energy conservation and environmental protection. Thus, in the wave of new technological revolution and industrial transformation, it should seize the opportunities of the times to achieve full integration with the new generation of information technology, promote the comprehensive transformation and upgrading of bridge industry, and then promote the development of the "third generation bridge project."

The main development direction of the third-generation bridge project is the "intelligent bridge." The development strategy of the intelligent bridge is highly compatible with the national strategic orientation and industrial pain points, and represents the development direction of bridge engineering. Demonstrating an ability to solve realistic problems will strongly support China in achieving the goal of becoming a world-leading bridge manufacturing country.

4. Development strategies of bridge engineering

4.1. Definition of an intelligent bridge

At present, no exact definition of an "intelligent bridge" exists. As the name suggests, the core of an intelligent bridge is the intellectualization of bridge construction and maintenance technology. Therefore, an intelligent bridge should contain three basic elements:

(1) **Bridge construction and maintenance technology.** This is a prerequisite for an intelligent bridge, since intelligent technology must adhere to advanced bridge technology in order to meet the actual needs of the bridge project. If the construction and maintenance technology is underdeveloped, intelligent technology in bridge engineering will be like a tree without roots.

(2) **Information technology.** Informatization is the basis of intellectualization, as intellectualization is required in order to establish a large-scale, top-down, and organized information network system. Therefore, the intellectualization of bridges is inseparable from the support of information channels. A scientific and unified information system can provide reliable data support for an intelligent bridge and will lay a foundation for the intellectualization of bridges.

(3) **Intelligent technology.** This is modern artificial intelligence technology that addresses bridge construction and maintenance. Intelligent technology is what will lead to the realization of bridge intellectualization, and to further expansion of the scope of bridge technology.

Thus, compared with a traditional bridge, an intelligent bridge has three basic characteristics: industrialization, informatization, and intellectualization. Among these, industrialization provides a complete industrial system for bridge construction and maintenance in order to achieve management standardization throughout the whole process of design, construction, and maintenance; informatization establishes an information channel for the entire process of bridge construction and maintenance, and realizes information standardization and digitization for the entire life of the bridge; and intellectualization builds an intelligent decision-making system for the entire process of bridge construction and maintenance, in order to reduce the reliance on manpower and realize unmanned bridge construction and maintenance.

It is clear that the development of an intelligent bridge requires guidance from two main aspects of development. The first aspect is the technology chain—that is, the integration of information intelligence technology with basic technologies such as bridge theory, materials, equipment, and software. By establishing interfaces with modern intelligent information technologies on various technical links, conditions of deep integration can be created for both intelligent technologies and bridge technologies. The second aspect is the industrial chain: Within the organizational management and coordinated development of the industrial chain, it is necessary to establish an institutional mechanism oriented to intelligent bridges in order to create a good development environment that will allow intelligent technology to penetrate into the bridge industry and further promote intelligent development of the technology chain.

In summary, the intelligent bridge is a new-generation bridge technology based on the full development of the bridge industrial chain, using the information channel created by modern information technology for the entire process of construction and maintenance, and formed from the integration of artificial intelligence with other intelligent technologies. Through intelligent design, construction, and management, the goal of safe, efficient, long-lasting, and environmentally friendly bridge engineering can be achieved.

4.2. Development focus of the intelligent bridge

Intelligent bridge technology is a new generation of bridge construction and maintenance technology that is based on the full development of bridge construction and maintenance technology, and formed from the integration of advanced technologies such as large data, cloud computing, the Internet of Things, virtual reality, and artificial intelligence. This technology has the capability to realize risk perception, rapid response, and intelligent management throughout the whole life-cycle of the bridge project. Furthermore, it can fundamentally promote technological innovation, management-mode innovation, and inter-enterprise collaborative management innovation during the whole bridge engineering life, including surveying, design, manufacturing, construction, operation, and maintenance. An intelligent bridge takes intelligent technology as its starting point; its construction will thus promote the development of basic bridge research, information supervision, intelligent decision-making, and life-time information-sharing technology, along with personnel training, technical exchange, and industrialization demonstration.

The development of an intelligent bridge involves various dimensions. Rather than being a simple matter of "intelligent technology + traditional bridge construction and maintenance technology," an intelligent bridge involves the restructuring of an industrial structure under the guidance of intelligent technology. Coordinated development of multiple industrial groups in areas such as bridges, materials, equipment, and information is required, and will drive changes in cooperation areas, modes, and mechanisms.

At present, sharing and collaborating has become a development trend that has gradually formed a social consensus and become a solution to former problems and new demands. The concept of "sharing" can serve as a foundation of common value for the integration of multi-industry innovation resources in the development of the intelligent bridge. Thus, it can help to solve industry pain points in the current technology system, such as low-level duplication, scattered resources, an entirely unformed industrial chain, insufficient transformation of results, and difficulties in multi-industry cooperation. In order to promote the sustainable development of the intelligent bridge and the bridge industry, a new "bridge ecology" must be built that is based on collaboration and sharing. The following three aspects of technology, platform and mechanism should be thoroughly undertaken:

(1) Developing bridge construction and maintenance technology in terms of industrialization, informatization and intellectualization;

(2) Establishing a national-level scientific development and industrialization platform for the entire industry chain;

(3) Exploring innovative modes for multi-industry collaboration in intelligent bridges.

In this way, sharing of demand, resources, and results can be achieved, collaborative innovation in the industry can be realized, and a bridge innovation system that is characterized by industrial chain innovation, platform innovation, and ecological innovation can be created.

4.3. Development suggestions for the intelligent bridge

In order to realize the intellectualization of a bridge, a three-step strategy involving a cultivation phase, implementation phase, and industrialization phase can be adopted. This strategy will promote the implementation of an intelligent bridge technology plan, and will significantly improve the industrialization, informatization, and intelligence level of bridges. The following work needs to be carried out in the development of bridge construction and maintenance technologies, in platform construction, and in the construction of an innovation mechanism, as detailed in the following three subsections.

4.3.1. Applying a key research and development plan for the intelligent bridge

Given the reality that the Chinese bridge industry lacks core technologies in terms of key technology and equipment in the sectors of design, manufacturing, construction, and maintenance, a scientific solution is urgently required. The key common and industrialization problems currently affecting bridge construction and maintenance technology and equipment can be broken through the top-level design of the system.

China's Bridge 2025 technological plan, which has the theme of the intelligent bridge, is the top-level technology development plan for bridge engineering in China over the next 10–20 years. In accordance with the principle of strengthening the top-level design and emphasizing integration of the whole industry chain, this technology plan starts from demand and covers the entire industrial chain of bridge design, construction, management, materials, equipment, and software. It includes three projects: Bridge Intelligent Construction Technology and Equipment, Bridge Intelligent Management Technology and Equipment, and a Bridge Integration Platform for Construction and Maintenance. Moreover, 29 projects (Fig. 3) are arranged according to basic frontiers, key common technologies, system integration, and industrialization demonstrations. Through deep integration between bridge construction and maintenance technology, and new-generation information technology such as the Internet, Internet of Things, big data, and cloud computing, research will be performed that focuses on intelligent-construction technology and equipment, intelligent-management technology and equipment, and an integrated platform for construction and maintenance. In addition, the corresponding research base and team building will be strengthened in order to create an innovation system for the entire bridge industry chain that is characterized by industrialization, informatization, intellectualization, and green construction, and to upgrade the bridge construction and maintenance technology and the industry's industrialization capabilities.

At present, the intelligent bridge has been listed as an extraordinary technical project of the China Communications Construction, making it the firstly carried out research project, determine a technical route for research work on the key projects of the future intelligent bridge, and consolidate the research foundation. At the same time, according to the new policy of national technology research, the China Communications Construction is actively developing a new project mode, which mainly depends on an enterprise's self-investment, and which is assisted with state support.

4.3.2. Building an intelligent bridge research and implementation platform

Prominent problems in the past have included the relative isolation of factors of technological innovation, a relatively low innovation platform level, an imperfect innovation system, and disjointed transformation channels for innovation achievements. Therefore, it is an urgent that China integrate its resources effectively, build a national-level technological innovation platform, and solve current difficulties with industry development.

For this purpose, the National Development and Reform Commission, the Ministry of Transport, and the China Communications Construction have jointly built a high-end platform: the National Engineering Research Center for the Construction of Long Highway Bridges. This is the only national-level technology research and industrialization platform for bridges in the domestic highway bridge industry. The center mainly focuses on the construction of national key projects and the needs of industry development; promotes businesses that align with the four development directions of bridge deep-water foundations, long-bridge structure systems and key structures, efficient bridge assembly, and long-bridge structural safety monitoring and detection and risk assessment; participates in the formulation of relevant technical standards; promotes international cooperation and exchanges; provides technical consulting services to relevant enterprises; and enhances the

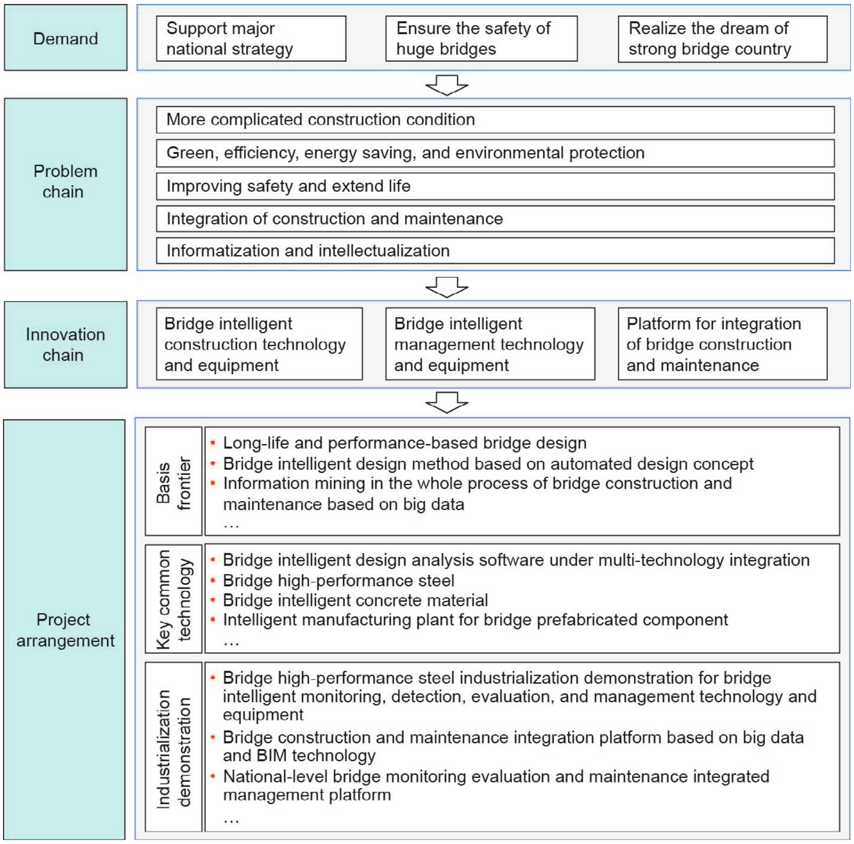


Fig. 3. Scheme of the intelligent bridge.

core competitiveness and innovation capability of China's bridge construction industry.

At present, the National Engineering Research Center for the Construction of Long Highway Bridges has begun operation. According to the relevant requirements of the state for the technology innovation platform, the center will be positioned as technological innovation and achievement transformation platform; concentrate on the development of key technologies for common industry and on the transformation and application of results; give full play to the driving role of technological advancement in the industry; and become an implementation platform, industrialization transformation platform, and talent cultivation platform for the key research and development plan of the intelligent bridge.

4.3.3. Establishing a new synergistic innovation mechanism for the bridge industry

In view of the problems in the field of bridge construction and maintenance in China, such as the unsmooth channels for the transformation of technological achievements, the imperfect marketization mechanism and cooperation mechanism of "production, study, research, and application," and the lack of secondary investment in the transformation of results, and the integration requirements of external innovation resources of "intelligent bridge" technology innovation, it is necessary to build a collaborative innovation mechanism for the bridge industry.

As mentioned above, based on the development concept of sharing and synergy, the combination of production, study, research, and application, and the principles of resource sharing, complementary advantages achieving, joint development, and collaborative win–win situations, it is necessary to integrate advantageous resources such as key enterprises, well-known universities, research institutes, and national and industry key laboratories and technology centers for bridges and related fields. Furthermore, it is necessary to establish the collaborative innovation platform for integration of construction and maintenance of long and large bridges, and to establish the bridge technology innovation strategic alliance (Fig. 4) for access to innovative resources inside and outside the industry at a higher level. The collaborative innovation mechanism is based on the inherent requirements of innovation development and the common interests of all parties involved; it follows the rules of the market economy and forms effective behavioral constraints and interest protection for members through legally binding contracts. It also establishes a sustainable and stable cooperative relationship among the industry, universities, and research institutes. In this way, the collaborative innovation mechanism will reshape the innovation ecology of the bridge industry.

In the coming period, the bridge collaborative innovation mechanism will mainly consist of two main bodies: the collaborative innovation platform for integration of construction and maintenance of long and large bridges orienting to the internal resources innovation of the industry; and the bridge technology innovation strategic alliance which will be directed by the "intelligent bridge" orienting to both internal and external resources innovation of the industry. A number of major scientific studies and engineering projects have been launched around the intelligent development of bridges, in order to organize and implement the future development of the intelligent bridge.

5. Summary

Over the past 40 years of China's reform and opening-up, bridge engineering in China has embarked on a successful path of independent construction and innovative development. A number of

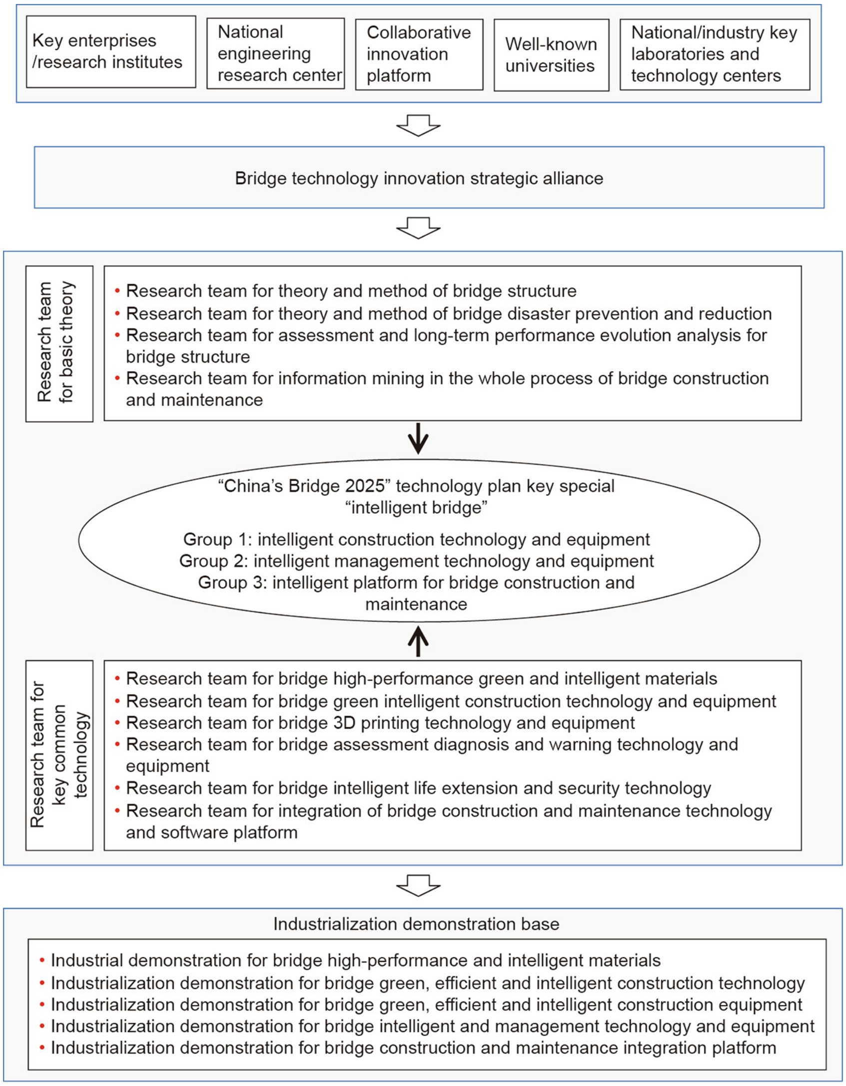


Fig. 4. A construction scheme for the Chinese bridge industry's bridge technology innovation strategic alliance.

independent innovations have been achieved, and a great number of bridges with international influence have been built. Furthermore, China has trained a number of leaders and technical experts in bridge engineering who have received many awards around the world, and who have won the respect and recognition of the international bridge industry. These achievements lay a solid foundation for China's future development as one of the world's foremost bridge-engineering countries. However, in comparison with developed countries, China's bridge industry still has problems to overcome: It lacks core technologies within key technological and equipment-related areas in the design, manufacturing, construction, and maintenance sectors, and it faces a series of deep problems with institutional mechanisms.

Enormous strategic, policy-related, and technological opportunities are currently available for bridge engineering in China, and the coming 10–20 years mark a period of important strategic opportunity for innovation, transformation, and upgrading in China's bridge engineering industry. In order to complete the three historical tasks of "supporting the national major development strategy, ensuring the safety and longevity of huge bridges, and realizing the Chinese dream of making China one of the world's foremost bridge engineering countries," China's bridge engineering industry must seize these opportunities and plan scientifically in order to implement the "intelligent bridge" technology plan and create the bridge technology innovation strategic alliance. In this way, China will guide the integrated development of intelligent technology, an industrialization system, and a specialized bridge-engineering platform, in order to upgrade Chinese bridge engineering toward the "third-generation bridge project," which is characterized by the "intelligent bridge." This shift will mark a leap forward in the development of the bridge industry.

Compliance with ethics guidelines

Xuhong Zhou and Xigang Zhang declare that they have no conflict of interest or financial conflicts to disclose.

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