Zhao et al. Advances in Bridge Engineering (2022) 3:29
https://doi.org/10.1186/s43251-022-00070-1

Advances in
Bridge Engineering

REVIEW

Open Access

State-of-the-art and annual progress of bridge engineering in 2021

Renda Zhao, Kaifeng Zheng, Xing Wei, Hongyu Jia, Xiaozhen Li, Qinghua Zhang, Guoji Xu, Yulin Zhan, Ruili Shen, Fang Zhang, Qianhui Pu, Hongye Gou and Chuanjin Yu*

*Correspondence:
ycj@swjtu.edu.cn

School of Civil Engineering, Southwest Jiaotong University, 610031 Chengdu, Sichuan, People's Republic of China

Abstract

Bridge construction is one of the cores of traffic infrastructure construction. To better develop relevant bridge science, this paper introduces the main research progress in China and abroad in 2021 from 12 aspects. The content consists of four parts in 12 aspects. The first part is about the bridge structure and analysis theories, including concrete bridge and high-performance materials, steel bridges, composite girders and cable-supported bridge analysis theories. The second part is about the bridge disaster prevention and mitigation, including bridge seismic resistance, vibration and noise reduction of rail transit bridges, monitoring and detection of steel bridge, hydrodynamics of coastal bridges, and durability of the concrete bridge under the complex environmental conditions. The last part is concerning the bridge emerging technologies, including bridge assessment and reinforcement, the technology in bridge structure test and intelligent construction and safe operation and maintenance of bridges.

Keywords: Bridge Engineering, Annual Progress in 2021, Review

1 Introduction

With the rapid development of China's economy, people's demand for the construction of infrastructure and transportation systems is increasingly high. Super-long sea-crossing bridges and high-speed railway bridges have been constructed and completed continuously. At the same time, the theory and method of bridge structure analysis, the design theory and calculation technology, the construction materials and other aspects are also developing and progressing, the theoretical level and technical application of bridge construction has reached an unprecedented height. As the length of high-speed railways continues to increase, the environment and conditions for building bridges are becoming more and more severe, such as fault zones, plateaus, frozen soil, and tsunamis. At the same time, the maintenance and evaluation of existing bridges, bridge big data and intelligent bridge construction are also emerging hot research directions in the field of bridge engineering. All these provide rich research topics and design challenges for bridge designers and researchers.

Over the past year, China's bridge construction has achieved fruitful results in many fields. In order to achieve more outstanding results in the future, it is necessary to analyze and summarize the progress of bridge research in the past year. The content consists of three parts in 12 aspects. The manuscript logic structure block diagram is shown in Fig. 1

The first part is about the bridge structure and analysis theories, including concrete bridge and high-performance materials, steel bridges, composite girders and the cable-supported bridge analysis theories. The second part is about the bridge disaster prevention and mitigation, including bridge seismic resistance, vibration and noise reduction of rail transit bridges, monitoring and detection of steel bridge, hydrodynamics of coastal bridges, and durability of concrete bridge under the complex environmental conditions. The last part is concerning the bridge emerging technologies, including bridge assessment and reinforcement, the technology in bridge structure test and intelligent construction and safe operation and maintenance of bridges. The manuscript will analyze and summarize the progress of bridge research according to these twelve areas in turn.

2 Advances in Concrete Bridges and its High-performance Materials

Concrete bridge is one of the most common bridge forms. This paper will mainly summarize and comment on the mechanical analysis, operation and maintenance, performance evaluation under the whole life cycle of concrete bridges, and high-performance concrete materials (fiber reinforced concrete: FRC; geopolymer concrete: GPC; ultra high-performance concrete: UHPC) and high-performance fiber reinforcement for bridges in the past year.

2.1 Research in concrete bridges

2.1.1 Research on the mechanical properties of concrete bridges

In 2021 there were many domestic and foreign scholars to study and improve the overall mechanical properties of concrete bridges and finite element simulation analysis methods.

For example, in the study of the mechanical properties of prestressed concrete bridges: Lantsoght et al. (2021) studied the shear capacity of prestressed concrete girders, and

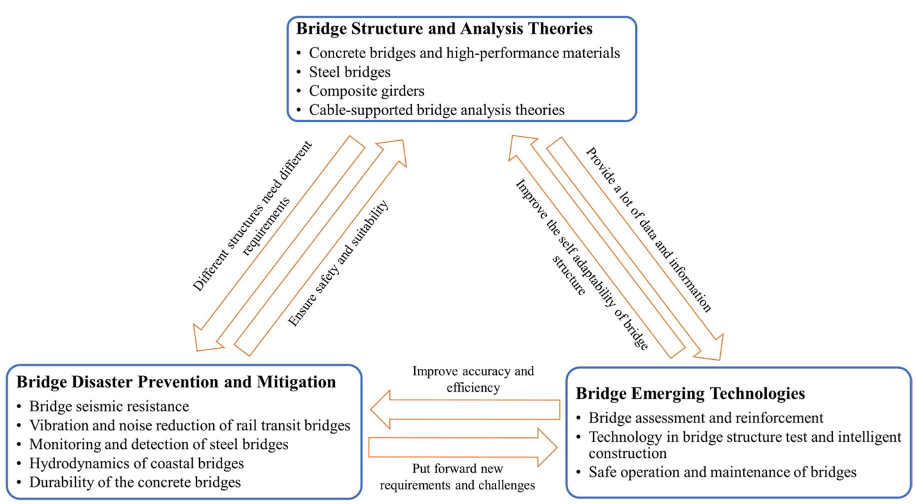

Fig. 1 The manuscript logic structure block diagram

failure mode was under discussion; Song et al. (2021c) proposed a reinforced concrete anisotropic intrinsic structure model combined with a layered shell theory approach to creating curved box section. In the area of seismic analysis studies of concrete bridges, Todorov et al. (2021) use.

d a non-linear finite element model of bridge piers based on fiber cells to investigate the effects of long-range ground shaking and near-fault ground shaking on the seismic performance of seismically designed piers.

2.1.2 Research on service and maintenance of concrete bridge

In 2021, great progress has been made in the operation and maintenance of concrete bridges in a variety of directions. Biswas et al. (2021) proposed a numerical model that can simulate the mechanical behavior of corroded reinforced concrete piers under earthquake. He et al. (2021g) proposed a method for evaluating the service performance of post-tensioned segmental box girder bridges based on cracks and applied it to the condition evaluation of two actual bridges. In addition, Chen et al (2021h) established a time-varying model of resistance degradation of ordinary reinforced concrete bridges to analyze the time-varying reliability of bridges under vehicle loads. Sun et al. (2022) studied the influence of frost heave damage on the mechanical properties of post tensioned prestressed concrete beams and its mechanism. Abdollahni et al. (2021) studied the fatigue life of concrete bridge pile foundations under the impact of waves.

2.2 Research on high performance concrete for bridges

2.2.1 Research on fiber reinforced concrete

In the past year, the research on fiber reinforced concrete (FRC) mainly focused on its working performance and mechanical properties, among which the research on mechanical properties was the most.

In terms of working performance, Yang et al. (2021a) and Wang et al. (2021q) both pointed out that the fluidity of the base material will decrease with the increase of the volume fraction and length diameter ratio of steel fiber, especially when the volume ratio of steel fiber exceeds 2% (Yang et al. 2021a), and the flexible fiber has a greater impact on the fluidity of concrete (Wang et al. 2021q).

In terms of the mechanical properties of FRC, relevant scholars studied the effects of fiber shape (Ran et al. 2021), size (Hassan et al. 2022), orientation (Chen et al. 2021d), content (Gao et al. 2021a) and type (Liu et al. 2021d) on the mechanical properties of the substrate. The research showed that the improvement effect of corrugated steel fiber on the tensile properties of the substrate was better than that of straight steel fiber and end hook steel fiber (Ran et al. 2021). When the fiber content was low (< 1.5%), the small-size straight steel fiber was better in improving the performance of the substrate, while when the fiber content was high, the hook shaped large-size steel fiber was better (Hassan et al. 2022). As the inclination angle of the fiber increases from 0° to 60°, the substrate would show greater and greater tensile ductility (Chen et al. 2021d). The 1.5% dosage value was the threshold dosage value of steel fiber to improve the fatigue life of concrete beams (Gao et al. 2021a). Steel fiber was more suitable for improving the strength of the substrate, while PVA fiber was better at improving the toughness of the substrate (Liu et al. 2021d), and so on.

In addition, some studies pointed out the advantages of hybrid fibers through the comparison of single doped fibers and hybrid fibers, such as the hybrid of steel fibers and basalt fibers (Lin 2021b), the hybrid of steel fibers and macro PP fibers (Feng et al. 2021a), and the hybrid of steel fibers, PVA fibers and $CaCO_3$ whiskers (Zhang et al. 2021j). These studies showed that suitable hybrid fibers could play a good synergistic performance. Through the above research results, it is not difficult to find that at present, the end hook steel fiber is still the mainstream research object of single doped fiber, but the research of hybrid fiber has gradually become a hot topic and is developing to the form of multi-scale hybrid fiber.

2.2.2 Research on geopolymer concrete

In the past year, the research on geopolymer concrete (GPC) was mainly focused on durability and engineering applications.

In the research of GPC durability, Sastry et al. (2021) found that adding nano-TiO_2 into GPC could improve the resistance to sulfate attack and chloride penetration. In addition, Saxena et al. (2021) pointed out that the mechanical properties and durability of GPC could be significantly improved by replacing part of natural fine aggregate with appropriate granite waste.

Some progress was made in the structural application research of GPC. Huang et al. (2021d) studied the response of GPC beams strengthened with basalt fiber (BFRP) tendons under impact load. The results showed that under the impact load, the failure mode of beams was generally the combined failure of bending and shear. Hadi et al. (2021) studied the effects of reinforcing bar types (steel bar and glass fiber reinforced bar GFRP) on the mechanical and deformation properties of GPC columns. The research showed that the failure of reinforced GPC specimen was firstly the buckling of longitudinal reinforcement, and then the fracture of longitudinal reinforcement or spiral reinforcement, which led to the complete failure of the specimen. However, the failure of specimens equipped with GFRP was caused by the kink of glass fiber in GFRP bars.

2.2.3 Research progress of UHPC

Ultra-high performance concrete (UHPC) has always been a research hotspot. Its research mainly includes material properties and structural applications.

In the study of mechanical properties of UHPC, Fan et al. (2021a) added steel slag powder into UHPC to improve the workability and chloride penetration resistance. Ahmed et al. (2021) and Yang et al. (2021b) mixed ground granulated blast-furnace slag into UHPC and the compressive strength of UHPC was increased.

In the research of structure and application of UHPC, Zhang et al. (2021p) proposed a predictive equation for calculating the shear capacity of RC composite beams using UHPC formwork based on the modified truss model theory. Wei et al. (2021c) studied the influence of hybrid fibers on the impact performance of UHPC beams. Based on the modified compression field theory, Feng et al. (2021c) established an analysis model of the shear capacity of prestressed UHPC beams under the combined action of bending and shearing, and obtained a simplified prediction formula for the shear capacity of UHPC beams.

2.3 High-performance reinforcement material for bridges

In 2021, a lot of progress was obtained in the research of FRP materials for Bridges. Cai et al. (2021b) proposed an innovative precast segmental bridge column (PSBC) system with fiber reinforced polymer (FRP) bar and steel bar as longitudinal reinforcement materials. The ductile failure mode of FSR-PSBC system was studied, and three damage limit states were defined in the process of ductile failure. Jia et al. (2021a) proposed a double-reinforced pier structure using fiber-reinforced plastic (FRP) bars and steel bars, and studied the ductility, post-yield stiffness and residual deformation of the pier structure. In addition, Kasiviswanathan and Upadhyay (2021) studied the buckling behavior of the web of a simply supported FRP box-beams under reverse load. Liu et al. (2021h) proposed an arch beam made of glass fiber reinforced polymer (GFRP) based on the latest curved-pultrusion technique.

3 Advances in Steel Bridges

The construction achievements and technological progress of large-scale and characteristic steel bridges built at home and abroad in 2021, such as the 1915 Canakkale Bridge, the Chibi Yangtze River Highway Bridge, the Zangmu Bridge crossing Yarlung Zangbo River, the Pi River Bridge, the New El Felden Railway Bridge in Egypt, and the Hanjiangwan Bridge in Wuhan is reviewed.

The new progress of research and application of new and special materials and components of steel bridges, such as steel for high heat input welding, weathering steel and high-performance steel, and welding materials for high toughness bridge weathering steel is summarized. The new progress of research and application of high-performance steel decks such as orthotropic steel bridge decks for annealing treatment after welding and non-destructive testing of weld fatigue cracking of steel decks is analyzed.

3.1 Construction achievements and technological progress of large and characteristic steel bridges

3.1.1 The longest-span bridge in the world: the 1915 Canakkale Bridge in Turkey

The 1915 Canakkale Bridge, the fourth connecting Eurasia between the Sea of Marmara and the Aegean Sea in Turkey was built, to commemorate the major events of the Turkish Ottoman Empire in 1915 (Crossing Continents 2022; "Wikipedia: 1915 Çanakkale Bridge" 2022). 1915 Canakkale Bridge is a twin-tower and three-span suspension bridge, two-way six-lane, with main span 2023 m, European shore Grimboru side and Asian shore Lapsecki side span are 770 m, the total length of 3563 m. The main girder of the bridge adopts a separate steel box girder, the height of the middle girder of the two boxes is 3.5 m, the horizontal net spacing is 9 m, and a beam with a width of 3 m and a height of 3.5 m is set every 24 m longitudinally, and 3 m maintenance lanes are set outside the box on both sides, and the total width of the beam body is 45.06 m; The whole bridge box girder is divided into 87 hoisting sections; The total height of the steel bridge tower is 318 m; The main cable adopts prefabricated parallel wire strand (PPWS, main span 288 bunches, side span 296 bunches); Gravity anchors with enlarged foundations are used, and the foundation of the bridge tower is a concrete caisson. The main bridge project and deck paving have been completed in 2021 (opened to traffic in March 2022, Fig. 2), becoming the world's longest span bridge, refreshing the bridge span world

Fig. 2 The 1915 Canakkale Bridge in Turkey

record of the Akashi Strait Bridge (1991 m span, completed in 1998) that has been maintained for 24 years, and is also the first important landmark bridge in the engineering history with a span of more than 2000 m.

3.1.2 The longest-span composite girder cable-stayed bridge in the world: the Chibi Yangtze River Highway Bridge

The Chibi Yangtze River Highway Bridge, on National Highway G351 from Taizhou to Xiaojin Highway, is a double-tower double-cable composite girder cable-stayed bridge with a span arrangement of (90 + 240 + 720 + 240 + 90)m, a main span of 720 m, and a height of 223 m and 217 m respectively for the south and north bridge towers, which will be completed and opened to traffic in September 2021(Liu and Zhang 2021; Zhang et al. 2019) (Fig. 3); The total width of the bridge deck is 36.5 m, and the composite girder structure composed of double-sided box girder and concrete deck; The height of the standard section steel girder is 3.18 m, and the lower flange adopts the form of widening and thickening, with a width of 2.45 ~ 3.20 m and a thickness of 32 ~ 70 mm, deck thickness is 26 cm. It is the world's longest-span cable-stayed bridge of fully composite girder.

Fig. 3 The Chibi Yangtze River Highway Bridge and its composite girder section

3.1.3 The longest-span plateau railway arch bridge in the world: the Zangmu Bridge crossing Yarlung Zangbo River

The Zangmu Bridge crossing the Yarlung Zangbo River is the largest double-track railway bridge in the Lhasa-Nyingchi section of the Sichuan-Tibet Railway, located in the upper reservoir area of sanga gorge and Zangmu Hydropower Station in the Yarlung Zangbo River, with a water depth of 66 m, a bridge site altitude of 3350 m, a total length of 525.1 m, and a docking tunnel on both sides of the strait; The main bridge is a truss arch bridge of concrete-filled steel tube with a span of 430 m, and an arch axial coefficient of 2.1 (Zeng 2019a) (Fig. 4); The diameter of the main arch truss string steel pipe is 1600 mm and 1800 mm, and the wall thickness is 24 ~ 52 mm; The steel pipe truss string adopts Q420qENH, and cross brace adopt Q345qENH paint-free weathering steel (the amount of weathering steel for the whole bridge is 12,800 tons); The string steel pipe is filled with C60 self-compacting and non-shrinkage concrete. The construction conditions of the Zangmu Bridge are extremely harsh, with a construction period of more than 5 years and will be completed and opened to traffic in 2021; It is the first large-scale railway coating-free weathering steel bridge on the plateau in China, accumulating many important experiences for the future construction of weathering steel bridges; It has become the world's longest-span plateau railway arch bridge and the world's 5th-long span railway arch bridge.

3.1.4 The longest-span navigable aqueduct bridge in the world: the Pi River Bridge

Anhui Province's navigable aqueduct bridge, the Pi River Bridge, the design flow rate is 150m^3/s, the water depth is 4 m (the verification water depth is 5.05 m), and the net width of the water crossing section is 32 m, which is an important water supply channel in Hefei City; Class VI waterway with 100t ships; The total length of the aqueduct is 350 m, of which the main bridge is (68 + 110 + 68)m steel continuous truss beam, with a total length of 246 m, using a separate double-through bridge; The water weight of the single-width bridge is about 19,800 tons, and the double-through water load is 1616 kN/m (nearly 135 times the highway Class I lane load). The steel of the whole bridge is Q345qD, Q420qD and 316L composite stainless steel, with a total steel consumption of 21,000 tons. The aqueduct bridge was completed in May 2021 (Ying et al. 2022) (Fig. 5); spanning slightly larger than the Magdeburg Water Bridge (57.1 + 106.2 + 57.1)m, with a total length of 220.4 m, a net width of 34 m, and a water depth of 4.25 m, completed in 1997), becoming the world's longest-span navigable aqueduct bridge.

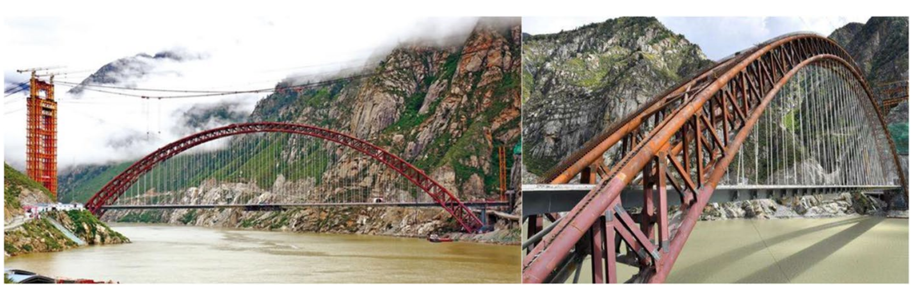

Fig. 4 The Zangmu Bridge crossing Yarlung Zangbo River

Fig. 5 The world's longest-span navigable aqueduct bridge: the Pi River Bridge

3.1.5 The longes-span open bridge in the world: the New El Felden Railway Bridge in Egypt

The main span of the new railway bridge spanning the East Channel of the Suez Canal in El Ferdan, Egypt is a biplane translational opening bridge of the (150 + 340 + 150)m double-track railway, and the design train is a two-line UIC 71 with a design speed of 80 km/h; Variable height steel truss girder and orthotropic steel deck are adopted, and the height of the fulcrum beam is 63 m; The amount of steel used is 14,700 tons; The diameter of the truss beam hinge on both sides is 18 m, weighing 400t, and the load bearing of the single hinge is 9000t; When the trusses on both sides are rotated around the hinge, a circular slide is set on the shore side to support the end of the truss beam (the translation process and the channel form a two-point support cantilever truss during the boat crossing process); The main project of the bridge was completed at the end of 2021 ("Wikipedia: El Ferdan Railway Bridge" 2022) (Fig. 6); with the same span as the El Felden Suez Canal West Channel Railway Bridge (a single-track railway, completed in 2001, now contracted by Chinese enterprises to transform into double lines and strengthened), and is listed as the world's longest-span opening bridge.

Fig. 6 The New El Felden Railway Open Bridge in Egypt

3.1.6 The first bridge using high-strength steel Q690 in China: the Hanjiangwan Bridge in Wuhan

The Hanjiangwan Bridge (the Seventh Bridge in Han River) in Wuhan, Hubei Province, adopts a steel truss arch bridge with a (132 + 408 + 132)m span, with a width of 47 m and 6 lanes in both directions (which can be widened to 8 lanes); Adopting the OSD and truss combined structure, top plate and welded U-rib full penetration technology, the lower chord rod of the midspan between the 3rd to 9th section arches with larger force is made of high-strength bridge steel Q690qE(plate thickness is 32 mm and 50 mm); The bridge was completed and opened to traffic in May 2021, and is the first large-scale bridge in China to use Q690-class high-strength steel(Du et al. 2021; Huang et al. 2020) (Fig. 7). High-performance bridge steels such as Q690qE have good application prospects.

3.2 Research and application of new and special materials and components of steel bridges

3.2.1 Steel for high heat input welding

High heat input welding of traditional low-alloy high-strength steel will reduce the toughness of its welding heat affected zone, and it is easy to produce welding cracks. Steel for high heat input welding can use much higher line energy than general conditions in welding, while the toughness of the welding heat affected zone is not significantly reduced and weld cracks are not easy to produce. *"Steel for high heat input welding (GB/T38817-2020)"* (State Administration for Market Regulation 2020) stipulates that the energy of this kind of steel welding is greater than 50 kJ/cm, and the yield strength range is 355 MPa ~ 500 MPa. Steel for high heat input welding mainly improves the toughness of the heat affected zone of low-alloy high-strength steel welding through two methods: reasonable composition design and oxide metallurgy technology (Wan et al. 2015).

Different elements have different influence laws on the properties of steel, therefore, the mass fraction of manganese and micro alloyed elements can be increased to improve strength; At the same time, the mass fraction of carbon is reduced to ensure weldability; The mass fraction of other unfavorable elements is controlled to ensure comprehensive performance; According to this guidance, the high heat input welding with economical, high strength, high toughness and excellent weldability is designed (Gu and Gu 2017). In addition, oxide metallurgy technology is more effectively applied in steel for large line

Fig. 7 The Hanjiangwan Bridge in Wuhan

energy welding: the oxide inhibits the growth of austenite and controls the transformation of the tissue during the welding process by forming a fine dispersion of fine inclusions, which can maintain the toughness of the rough crystal region of the steel for large line energy welding at a better level.

At present, steel for high heat input welding is mainly used in infrastructure and large-scale buildings such as ships, marine engineering, construction, oil storage tanks and bridges; The steel shell project of the immersed tube tunnel of Shenzhen to Zhongshan Channel uses steel for high heat input welding for the first time, and the maximum strength of the steel plate is 420 MPa, the maximum thickness is 40 mm, and the maximum welding line energy is 270 kJ/cm, which marks a new breakthrough in the research and application of steel for high heat input welding in China (Wang et al. 2019).

3.2.2 Weathering steel and high performance steel

Traditional weathering steel usually contains higher Cu, P, Ni and other elements to improve its corrosion resistance. Studies have shown that the corrosion-resistant weathering steel in the marine environment, Mo element can form MoO_2 and MoO_3, which can promote the conversion of γ-FeOOH α-FeOOH to improve its corrosion resistance (Sun et al. 2021a). Fu et al. (Fu et al. 2021a) studied the corrosion properties and rust layer material of Q345qDNH by conducting accelerated corrosion tests that simulated the industrial atmosphere, and the results showed that the weathering steel had higher corrosion resistance in the atmospheric environment. In addition, Xu et al. (2021h) also studied the effect of weathering steel resistance on corrosion resistance in the marine environment, and the results showed that Al and Mo elements can improve the stability of weathering steel rust layer in marine environment and improve the corrosion resistance of weathering steel. Zhou and Yang (2021) conducted a study on the crack development of the rust layer of weathering steel, and the results showed that the rust layer inside the weathering steel had higher thermal shock resistance than the outer rust layer. Due to the alternating occurrence of the increase in the depth of corrosion and the lateral expansion, its surface rust layer consists of an alternating band-like structure parallel to the interface. Corrosion resistance studies of weathering steel have shown that after improvement, it can have higher corrosion resistance and adapt to more extreme environments; In addition, the corrosion-resistant steel also needs to have sufficient mechanical properties and fatigue strength to be better applied to the bridge. Shi et al. (2021a) carried out the full-scale model test and detailed fatigue test of the A709 Grade 50CR steel composite beam, using a uniform corrosion model to consider the reduction of the mechanical properties and fatigue strength of the composite girder bridge under the condition of uniform weakening of the cross-section. Guo et al. (2021a) conducted a high-cycle fatigue test on the Q690 high-strength steel after accelerated corrosion, and the results showed that the mass loss rate of 100 days of corrosion was 7.21%, and after 60 days of corrosion, the fatigue limit of the specimen was reduced by 30.15%. Zhang and Zheng and others (2020b, 2021w) carried out large-scale fatigue performance tests after corrosion of weathering steel and high-performance steel, studied the corrosion properties and fatigue properties of weathering steel Q345CNH and high-performance steel HPS 70 W in the marine environment, and the results showed that with the increase of corrosion time, the uniform corrosion amount and pit erosion depth of the two steels increased, and the corrosion test environment can be used to simulate the marine environment of C3 in China, and both steels have good corrosion resistance; At the same time, the fatigue strength of the two steels after corrosion has a certain degree of decline, the longer the corrosion time, the greater the amount of fatigue strength decrease, the fatigue strength of the corrosion 180 cycle Q345CNH and HPS 70 W decreased by 38.3% and 35.7%, respectively.

3.2.3 Welding materials for high toughness bridge weathering steel

As required by other applications, weathering steel for bridges needs to have a matching weld material to ensure that the weld has sufficient mechanical properties and fatigue strength. In recent years, with the continuous improvement of the application potential of weathering steel in the field of bridge engineering, the research and development of welding materials for high-toughness weathering steel has achieved certain results, overcoming the problems of relying on imports, high cost, complex production process, long cycle and mismatch between supply and demand operation standards in the past. Three types of welding materials for high-toughness bridge weathering steels developed by Li et al. (2019), including HTJ-507 CrNiCu electrodes, HTW-550GN gas shielded welding wires, HTM-550GN submerged welding wires and HTF-101GN submerged solitary welding flux, etc., under the premise of ensuring that the mechanical and corrosion resistance meet the requirements, they also meet the requirements of the weld seam for low temperature impact toughness; For the 3 types of the welding materials of the weathering steel for bridges, according to the "Atmospheric corrosion resistant steel and stainless steel welding materials for railway vehicles (TB/T2374-2008)" and other standards for process evaluation and periodic infiltration corrosion test, its mechanical properties, atmospheric corrosion resistance, low temperature toughness of -40 °C and other properties are qualified, to meet the requirements of Q345qENH and Q370qENH weathering bridge steel, the test shows that after 100 h of infiltration corrosion they still has good corrosion resistance.

3.3 Research and application of high-performance steel bridge deck

3.3.1 Orthotropic steel deck with annealing treatment after welding

The structure of the steel deck is complex, the welding residual stress is relatively large, and the fatigue stress amplitude caused by the action of the vehicle load is also relatively large. Under the superposition of residual stress of welding and load stress, after a certain period of service, weld fatigue cracking often occurs on the steel deck. Annealing treatment after welding has the characteristics of mature process and low requirements for processing equipment, and most of the production of pressure vessels and pipeline equipment have the requirements of this process. In addition to reducing the residual stress of welding, the process can also improve the microstructure and properties of the lattice of the welded joint and its heat affected zone, appropriately reduce the hardness, improve plasticity and toughness, further release harmful gases in the weld, prevent the occurrence of hydrogen embrittlement and cracks in the weld, and stabilize the geometry of the components. As an exploratory study, Feng et al. (2022) have carried out preliminary research on the fatigue performance of annealing steel deck after welding in recent years (Fig. 8), including the test of residual stress, the comparative fatigue

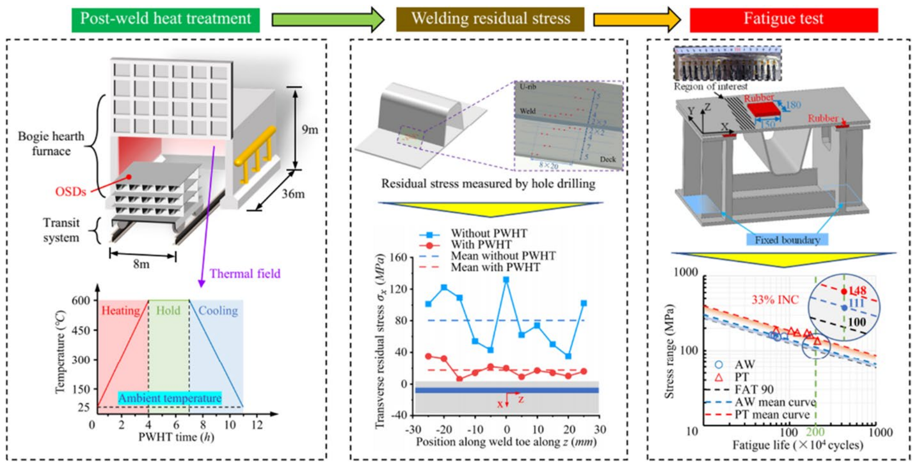

Fig. 8 Study on fatigue resistance of annealed steel deck after welding

experiment of the full-scale model and the simulation analysis of the influence mechanism. Among them, the residual stress test based on blind hole method and X-ray diffraction shows that the weld residual stress of the welding surface of the top plate and the longitudinal rib of the steel deck is reduced by more than 76% annealing treatment after welding; Comparative fatigue experiments show that due to the reduction of residual stress of welding for annealing treatment, the fatigue strength of the weld seam of the top plate and the longitudinal rib can be increased by more than 23%. In addition, numerical simulation based on fracture mechanics shows that the reduction of residual stress can effectively delay the germination of fatigue cracks and reduce the rate of crack propagation, thereby improving the fatigue strength of welds.

Based on the above research results, annealing steel deck after welding has been applied to the 7th steel box girder bridge of the reconstruction project of Susong Road in Hefei City. The bridge is a 4 × 37 m continuous girder with a deck width of 25.5 m and a girder height of 1.6 m (Fig. 9). The bridge became the first bridge to apply annealing steel deck after welding in the world.

3.3.2 Nondestructive testing of fatigue cracking of welds on steel decks

How to find and effectively evaluate the fatigue deterioration of steel decks in service has become the focus, difficulty and hot spot of current research. Some researchers at home and abroad have proposed a series of nondestructive testing methods for fatigue cracks, including acoustic emission, recognition of digital images, detection of spontaneous magnetic leakage, and detection of infrared thermal imaging. Duan et al. (2020) used acoustic emission technology to carry out fatigue crack detection on the Weihe Bridge and Hangzhou Bay Bridge and continuously monitor the expansion process; Xu et al. (2019) combined digital image technology and deep learning methods to realize the intelligent monitoring of fatigue cracks on the surface of steel structures; Zhou et al. (2021b) proposed a method for detecting fatigue cracks based on the spontaneous magnetic leakage signal of metals, which realized effective crack localization and propagation

Fig. 9 The steel box girder bridge applied to annealing steel deck after welding of the Susong Road Reconstruction Project in Hefei City

monitoring. In addition, non-contact non-destructive testing of thermal imaging technology used by Yoshiaki et al. (2018) is particularly distinctive (Fig. 10). From the local temperature difference generated by cracks, this method can use the equipment of simple infrared thermal imaging to achieve efficient and high-precision detection of weld cracking under insolation conditions.

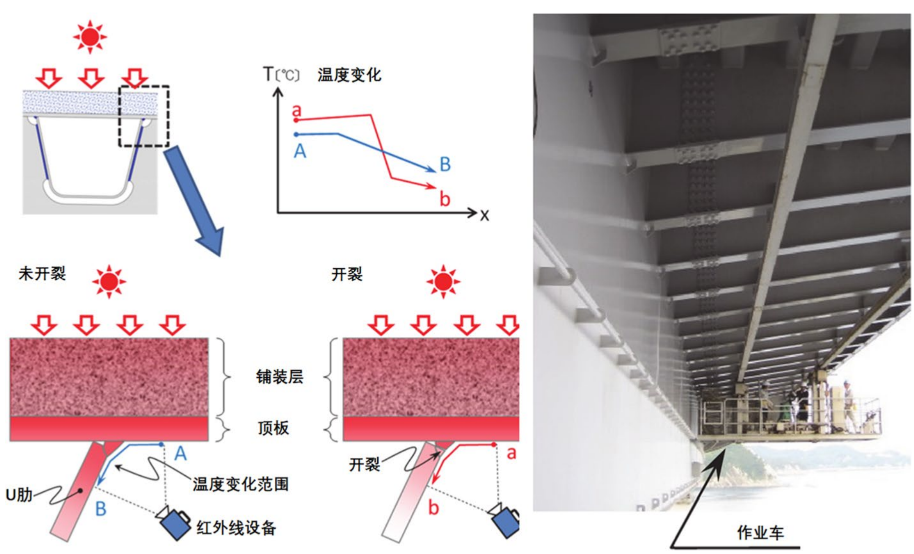

Fig. 10 Principle and implementation of non-contact flaw detection of welds based on infrared thermal imaging

4 Advances in Composite Girders

The steel–concrete composite structure has been widely used in many fields of bridge engineering, because of the reasonable load transfer, economic efficiency, and ease of construction. Some promotions are achieved in Chinese constructions. Researchers studied detailed specimens, like shear connectors, and the mechanical behavior of the composite bridges.

4.1 Research on shear connectors

Different types of connectors are studied, including stud connectors, high-strength bolt connectors, PBL connectors and other improved connectors. The researches of high-strength bolt connectors, and other improved connectors are more than in the last year.

Push-out tests and FE simulations are conducted, which focuses on the following three parts. First, the geometric design of single connector and group connectors is studied. The ultimate capacity, deformation relationships, failure modes and predicted formulas are discussed. Secondly, the fatigue performance about degradation of shear stiffness and endurance prediction is studied. Thirdly, shear performance under complex environments is referred.

Cai et al. (2021a), Hu et al. (2021a), Ding et al. (2021a), and Wang et al. (2021n) conducted push-out tests of group connectors. They have the consistent results on the effects of these factors such as the diameter, the shank length, the concrete capacity, the slab thickness and the spacing. Some applications with the high-performance concrete are studied by Ding et al. (2021a), Wang et al. (2021n). Huang et al. (2021c), Zhao et al. (2021c), Xu et al. (2021e) and Li et al. (2021c) concentrated on the application of connectors with the short shank, the large diameter and thin concrete slab. The fitted slip curve is proposed by Huang et al. (2021c) and different failure modes are discussed based on different ratio of length to diameter by Zhao et al. (2021c). Zhang et al. (2021i) and Hu et al. (2021b) conducted experiment on the single shear connector. Hu et al. (2021b) proposed theoretical model with the wedge block to describe the destructive process and predict the capacity. Besides the above factors, Zhan et al. (2021b) emphasized the effect of the weld collar. Su et al. (2021b) studied the studs covered by rubber. Fracture mechanics are applied on the evaluation of fatigue performance. Shi and Li (2021), Xu et al. (2021i) and Wang et al. (2021a) studied the stress intensity factor on two paths, the bottom of the wed collar and the interface of the weld collar and the shank. Sjaarda et al. (2021) discussed the redundancy of the shear connectors under cyclic loads caused by the system reliability. Xu et al. (2021c) mixed the methods of the strain measurement and the ultrasonic testing to observe the crack promotion. Complex environments contain fire (Tian and Ožbolt 2021), corrosion (Xu et al. 2021g), earthquake (Suzuki and Kimura 2021) and extremely low temperature (Xie et al. 2021), which always leads to the combination of the axial and shear forces (Zhuang et al. 2021).

As for high strength bolt connectors, influences of the strength of concrete, the bolt size and grade (Wang et al. 2021s), the hole clearance (Hosseini et al. 2021), the prestress (Tzouka et al. 2021), on the shear strength and the load-slip curves are explored. Yang et al. (2021f), Ataei and Zeynalian (2021) studied the stress redistribution and failure. The effect of fibers in the concrete is studied when under the cyclic loads by Chiniforush et al. (2021) and He et al. (2021c).

PBL connectors have different application scenarios. The lateral force (Wang et al. 2021t), different types of concrete (Wu et al. 2021a) and group effects of PBL (He et al. 2021c; Wang et al. 2021r) are discussed and the prediction of capacity is proposed by Wu et al. (2021a). Liu et al. (2021i) studied the shear performance and pull performance. Suzuki et al. (2021) proposed the equivalent shear area to describe and predict the shear failure.

Improved connectors are designed for special functions mostly, such as Omega type connectors by Tabet-Derraz et al. (2021), Y-type bar connector by Kim et al. (2021a) and Kim et al. (2021b), MCL connector by Kong et al. (2021) and adhesive shear connectors by Zhan et al. (2021a). Channel connectors are applied to solve the problem of CSW construction by Jiang et al. (2021c). Maghaghi et al. (2021) and Arévalo et al. (2021) studied the static and fatigue performance of channel connectors as well. Prefabricated shear studs were studied by Gao et al. (2021c). Because of the complex mechanical behavior in the hybrid section, the steel–concrete joint was studied by Yao et al. (2021b), Shi et al. (2021c) and Zou et al. (2021b) in different constructions. Kruszewski and Zaghi (2021) conducted experiments of the above traditional connectors.

4.2 Research on steel–concrete composite girders

Five parts of research on steel-composite girders are collected. First, the theoretical analysis and numerical methods for simplifying calculations of the mechanical behavior of composite girders are studied. Secondly, spatial mechanical behaviors, containing the combination of moment, torsion and shear are referred, as well as the curve beams. Thirdly, the performance of composite girders on the negative moment zones and the treatments about improving such performance are explored. Fourthly, the performance of composite girders under the long-term and complex environments, such as cyclic loads, temperature loads, fire and creep and shrinkage of the concrete are discussed. Fifthly, researches on the construction process and construction method are conducted.

The methods of variation and balanced equations are applied in calculation deformation and stress, considering slips, shear deformation, shear lags by Wu et al. (2021b), Wu et al. (2021c), Ji et al. (2021), Xie et al. (2021), Zhou et al. (2021e), Yang et al. (2021f), Benyahi et al. (2021) and Gara et al. (2021). Theoretical solutions about temperature loads are derived by Chen et al. (2021a), Wang et al. (2021i). The torsion stiffness is studied by Qin et al. (2021a), based on the second theory of Umanskii.

Other studies include the features of shear connectors by Kamar et al. (2021), Daou et al. (2021), Vigneri et al. (2021) and Alsharari et al. (2021a), the arrangement of concrete slabs by Xie et al. (2021) and prestress reinforcements by Lou et al. (2021), Xiao et al. (2021a), the application of UHPC by Zhu et al. (2021a), Du et al. (2022), Wang et al. (2021x) and Xiao et al. (2021b), and other factors influence the spatial mechanical behaviors of the composite bridge. Nicoletti et al. (2021) studied the effective width detailedly on the studs, the section configurations, and the span. Zhou et al. (2021h) studied the composite girders made by stainless steels under the combination of moment and shear, and proposed a method to evaluate shear capacity. Lin (2021a) studied the performance under the combination of moment and torsion. Liu et al. (2021k) explored the effects of different angles and connector types on the torsion. Sadeghi et al. (2021) created a monitoring system for measuring slips at steel–concrete interface. Shao et al.

(2021b) proposed a design scheme of steel-ultra high-performance concrete composite truss arch with main span of 1000 m. As for corrugated steel webs (CSW), there are many applications and studies on the deformation characteristics. Zhou et al. (2021d) proposed a new type of corrugated webs by simulating the forewing of the allomyrina dichotoma. Wang et al. (2021p) improved the elastic buckling prediction formula. Ji and Liu(2021) explored the elastic buckling behavior of CSW with variable sections. Dong et al. (2021) and Cheng et al. (2021c) studied the flexural behavior under the negative and positive moment of the truss beam and the composite deck, respectively. Deng et al. (2021) and Zhu et al. (2021f) studied the torsion deformation and performance of the composite box girder with CSW.

The composite beams perform differently compared with those under the positive moment, because of the influence of cracks propagation in the negative moment zones. The treatment and reinforcement of cracks are paid more attention to, such as the application of UHPC and prestressing tendons. Hu et al. (2021c) studied the influence on the cracking loads by the prestressing tendons in detail. Su et al. (2021a) explored the application of the studs with rubber to reduce the concrete stress on the mid-supports. Luo and Ma. (2021) studied the mixture of UNPC and NC on the deck of composite girders. Wang et al. (2021g) studied the continuous girder with UHPC concrete deck and observed the short and crowded cracks. Wang et al. (2021f) compared the performance of the effect of UHPC and prestressing tendons on the composite beams under the negative moment. Zhou et al. (2021g) emphasized that elevating the thickness of the concrete slab is better than increasing the reinforcement ratio on the shear capacity. Nasiri et al. (2021) studied the reinforcement effect of prestressed beams on cracked steel–concrete beams. Xu et al. (2021a) studied the effect of the steel fiber in the concrete and compared different arrangements of studs. Men et al. (2021a) and Men et al. (2021b) conducted experiments on simple composite girders under negative moments and shear forces, considering the ratio of the moment and the vertical force, the reinforcement ratio, the web buckling and the interaction degree of the shear connectors.

The performance of composite girders under fatigue loads and complex environments is focused by many researchers. Wang et al. (2021aa) found the local stress and the shear buckling on the irregular corrugated webs and detected the beginning of the fatigue cracks by conducting fatigue tests. Hassanin et al. (2021) studied the composite girders with the external prestressing tendons under fatigue loads and the effect of different interaction degrees of the shear connectors. Alsharari et al. (2021b) studied the composite girders with three pre-damaged situations, including the influence of external environment, cyclic loads and static overloads. The cracking patterns under these situations were compared. Ma et al. (2021b) simulated the fatigue damage propagation of the deck, based on the experiment of the steel-UHPC composite girder. Tu et al. (2021a) studied the fatigue performance of the composite girder with the concrete filled steel tube and the corrugated webs. The fatigue cracks were classified. Chen et al. (2021a) tested ten steel–concrete composite girders under accelerated corrosion. Hamid et al. (2021) studied the influence of temperature on the internally cured concrete and normal concrete on the cracks. Zhang et al. (2021g) simulated the continuous bridge under fire, and studied the influence of the fire intensity and the exposure locations. Song et al. (2021a) studied the curved beam under local fire, and recommended that the web buckling could be the failure criterion. Zhang et al. (2021d) monitored the temperature of the real bridge, and proposed the formula about the temperature along the section. Wang et al. (2021b) simulated the vertical gradient of the temperature. Fan et al. (2021b) conducted the indoor baking radiation test of the composite girder by using the lamp, and analyzed the temperature distribution of the beam. Zhu et al. (2021d) tested 4 simply supported curved beams and 1 continuous curved beam for 222 days under constantly distributed loads. The vertical, rotation and slips were collected, and the effect of creep and shrinkage of concrete on the stress redistribution of the stress was studied.

Researchers focused on the processing analyses, because of the uncertainty during the construction and different mechanical behavior with the completed state of bridges. Zhang et al. (2021e) compared the influence of the weight of the steel main beam, the bridge deck weight, the elastic modulus of the cables and the temperature on the behavior of the long-span cable-stayed bridge in the completed bridge state. Zhu and Zhu (2021) studied the problem of distortion of steel tube-girder with top flange bracing considering warping restraint effect. Abo El-Khier and Morcous (2021) conducted experiments on the wet joint made by UHPC and loop einforcements. Yuan et al. (2021d) studied the shear lag effects during construction of the cable-stayed bridge with corrugated steel webs. Wang et al. (2021u) proposed a method to predict the deflection of the prestressed concrete rigid frame bridge with corrugated webs, by combining FE simulations and algorithms of MEC and BP.

5 Advances in Cable-Supported Bridge Analysis Theories

Two topics are summarized in this area according to the reports in 2021, including the analysis theories for members of cable-supported bridges and refined analysis method of connecting components.

5.1 Analysis theories for cable, tower and girder

5.1.1 Analysis theories for cable

Several representative works on the main cable alignment and construction control of traditional suspension bridges can be found in 2021. Luo et al. (2021b) presented on the high-precision calculation method of the cable alignment of suspension bridge with pinned cable clamps. Qi et al. (2021) proposed a new cable network structure (Fig. 11) to improve the wind-resistant performance of narrow suspension bridge. They proposed a multi-point cable element that can consider the movement of pulleys. The results show that this method can be adopted for the analysis of cable net suspension bridges with pulley blocks. Li and Liu. (2021) proposed an improved continuous beam model for the construction process calculation of long-span suspension bridges. Zhou et al. (2020) presented an analytical method for the main cable deformation of the suspension bridge under the temperature effect. The method has been verified by the monitoring data of the Tsingma Bridge. Wang et al. (2021v) proposed a form-finding method for a new type of spatial self-anchored hybrid cable-stayed suspension bridges.

The cable calculation of multi-span suspension bridge was also widely concerned in 2021. Zhang et al. (2021t,r,s,q) carried out relevant investigations on the simplified calculation model, construction stage analysis, and vibration characteristics of multi-span

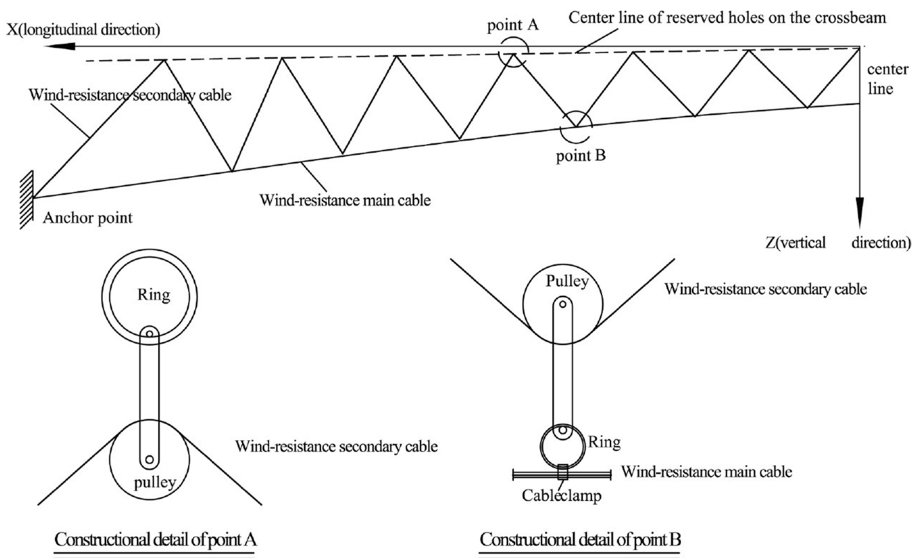

Fig. 11 Pulley-connected cable net system

suspension bridge. Cao et al. (2021) used a simplified model to investigate the static characteristics of the three-tower suspension bridge with central buckles.

5.1.2 Stability theory for tower and girder

Stiffeners are adopted for the steel bridge members to increase the rigidity and strength. The stiffened box section members are widely used in cable-supported bridges. Gui et al. (2021a) carried out compressive load tests on stiffened steel members with extended flanges and presented a calculation method for the elastic buckling coefficients of the stiffened extended flange supported on three sides using the energy principle. Taking the Changhong Bridge, a self-anchored suspension cable-stayed bridge, as background, Wang et al. (2021d) carried out compression loading on a 1:4 scale steel box girder experimental segment to investigate the full-range mechanical behavior. Wang (2021e) also presented eccentric compression tests on full-scale stiffened plates with U-ribs and discussed the influence of the number of stiffeners on the ultimate bearing capacity. Bai et al. (2021) put forward a new highly efficient method for nonlinear analysis for large stiffened box members including local buckling, named as the progressive-models method. The local buckling effect was simplified by the average stress–strain curve of the stiffened plate. The method can be also extended to the structural system.

Modern technology can manufacture curved stiffened members with ease. Ljubinković et al. (2019) carried out a stability test and numerical simulation on a steel box girder (Fig. 12) of which the bottom plate is curved. Staen et al. (2021) employed the shell finite element model to investigate the elastic shear stability of curved steel webs.

After the successful application of Q500 high-performance steel in the Hutong Yangtze River Bridge, the Wuhan Hanjiang Bay Bridge completed in 2021 adopts a new generation of high-strength bridge steel Q690 (Yi et al. 2021). With the improvement of steel strength, the design of stability for large steel bridge members will face new challenges.

Fig. 12 Steel box girder with curved stiffened plates at the bottom

The Changtai Yangtze River Bridge adopts a high-rise diamond-shaped steel–concrete hybrid tower of which height is 340 m. The upper tower legs are steel–concrete composite sections, and the middle and lower tower legs are concrete box sections. Huang et al. (2021b) investigated the applicability of the eccentricity magnifying coefficient specified in the design codes to the complex bridge tower structure. They recommended the use of the line finite element model for the reinforcement design of the bridge tower and pointed out that a refined finite element model should be adopted for the analysis. Yuan et al. (2021c) obtained the eccentricity magnifying coefficient available for the bridge tower using theoretical derivation and numerical analysis. Due to the complex mechanical behavior of inclined pylons or curved pylons in asymmetric span bridges, Jutila et al. (2021) proposed an analytical algorithm for the conceptual design, which was used in the analysis of single tower cable-stayed bridges with harp-shaped cable arrangement.

The stability of large concrete bridge towers has been concerned. In recent years, topics related to analysis of concrete bridge towers have been frequently reported. The methods adopted are mainly the line and the solid finite element method. However, the above research is mainly for some actual projects, thus the adopted models still have limitations. For similar structural details of the same type, BIM Technology can be introduced to build a parametric module of large concrete members, so as to facilitate the parametric analysis of the mechanical performance of the members and optimize the design of the structure with high efficiency.

5.2 Analysis theories for connecting components of cable-supported bridges

5.2.1 Analysis theory for saddle and saddle-cable system

To realize a highly efficient calculation for the lateral pressure between the main cable and the saddle groove, Wang et al. (2021j) proposed the strand element method (Fig. 13) for the main cable strands of 37-, 61-, 91-, and 127-wires. The method was validated against the test. An actual multi-span suspension bridge was analyzed by this method. The results showed that the proposed method could be directly applied to the sliding resistance design of the main cable.

Zhong et al. (2021) adopted finite a element model to investigate the ultimate bearing capacity of the cable saddle. The effects of material strength, the thickness and number

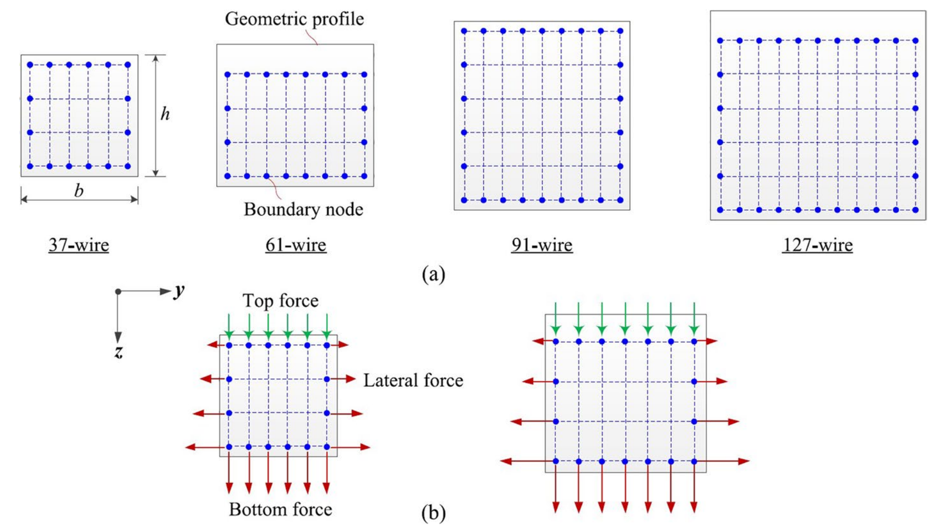

Fig.13 Strand element method for the lateral pressure between the main cable and the saddle groove

of transverse stiffeners, the width dimension of the saddle groove, the thickness of saddle groove, and the longitudinal stiffeners on the ultimate bearing capacity of cable saddle were investigated through the elastoplastic analysis.

The Hutiaoxia Jinsha River Bridge is a single tower ground anchored suspension bridge. One side of the main cable is anchored into the rock through a new type of composite cable saddle, which has the both functions of the main saddle and the splay saddle. Liu et al. (2021a) introduced the design.

5.2.2 Slip resistance analysis method for clamp

The mutual sliding between the cable clamp and the main cable has occurred in the suspension bridges operated for many years. One reason is that traditional empirical formulas for sliding resistance design of cable clamp could not fully consider the interaction between the main cable and the clamp.

Miao et al. (2021b) simplified the cable clamp to a plane model. Based on the equilibrium conditions of the plane microelement of the cable clamp, both the explicit formula for the contact pressure between the main cable and the cable clamp and the formula of the sliding resistance were given. The furrow effect exists when the main cable and the cable clamp squeeze each other, resulting in different friction behaviors of the cable clamp plane micro elements along the radial and axial directions of the main cable. For this reason, two independent friction coefficients were considered. Subsequently, the deduced formula was verified by the solid finite element model.

For the pin-hinge type cable clamp, the contact pressure between the cable clamp and the main cable is generated by tightening the screws. It is difficult for the multi-row screws in the cable clamp to be tightened synchronously (Fig. 14) due to the interrelationship of tightening force between screws. Miao et al. (2021a) investigated the interaction effect of cable clamp screw fastening and proposed the fastening optimization method. The tightening optimization method was based on solid finite element model. The test result of an actual bridge showed that the proposed optimization method could

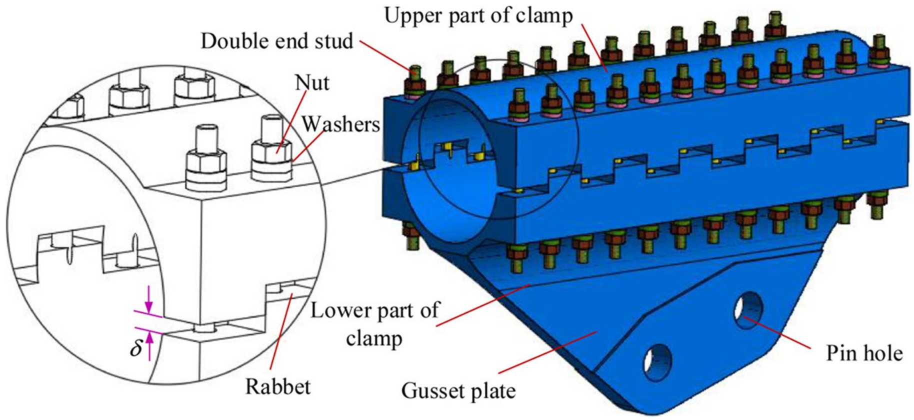

Fig. 14 Multi-row screw arrangement for cable clamps

not only obtain uniform screw force, but also reduce the number of times of screw tightening, so as to reduce the on-site labor.

6 Advances in Bridge Seismic Resistance

In order to promote the development of bridge engineering, on the basis of consulting a large number of literatures, this part systematically combs many achievements in the field of bridge earthquake resistance in 2021. The search literatures are mainly from domestic and foreign well-known journals such as Engineering Structures, Journal of Bridge Engineering, Soil Dynamics and Earthquake Engineering, Earthquake Engineering & Structural Dynamics, Journal of Structural Engineering, Journal of Southwest Jiaotong University. The research on the seismic field of bridges in 2021 can be summarized as the following four aspects: (1) the study of seismic performance of bridge piers; (2) collision and contact problems; (3) bridge seismic isolation technology; (4) seismic response and seismic evaluation of bridges.

6.1 Seismic performance of bridge pier

6.1.1 Seismic performance of traditional monolithic cast bridge pier

This year, the research on the seismic performance of integral cast piers is mainly focused on RC piers and new material piers. For RC piers, scholars (Aboukifa and Moustafa 2021; Amirchoupani et al. 2021; Ding et al. 2021b; Liang et al. 2021b; Mehrsoroush and Saiidi 2021; Xu et al. 2021d) discuss their effects on the seismic performance of RC piers according to the factors such as wall-thickness ratio, corrosion, steel bar strength and damage state boundary through experiments and numerical simulation. For the new material bridge pier, the researchers (AL-Hawarneh and Alam 2021; Li et al. 2021e) mainly improved the concrete material, and discussed the seismic performance of the bridge pier made of ultra-high performance concrete, recycled aggregate concrete and fiber reinforced concrete respectively.

6.1.2 Seismic performance of reinforced pier

Scholars (Cai et al. 2021b; Jia et al. 2022; Wang et al. 2021o; w; Zhang et al. 2021o) mainly used the reinforcing materials such as carbon fiber reinforced polymer (CFRP) to improve the plastic hinge area of bridge piers for corrosion, cracks and other local damage areas (Fig. 15) and proposed a precast concrete pier seismic strengthening method (ASRM) based on carbon fiber reinforced polymer (CFRP) and polyethylene terephthalate (PET) materials. And the sensitivity analysis method of engineering cement composite material (ECC) is used to study the seismic performance of pier bridges strengthened with ECC.

6.1.3 Seismic performance of prefabricated and self-resetting piers

For prefabricated piers, scholars (Benjumea et al. 2021; Liu et al. 2021g; Qu et al. 2021; Shoushtari et al. 2021; Wang et al. 2021m; Xu et al. 2021f; Zhang et al. 2021f) mainly focused on their connection modes and load types. There were many researches on the connection mode of grouting sleeve. The types of loads, biaxial excitation, combined transverse torsional load and explosive load have been studied. The results show that the seismic performance of prefabricated piers is similar to that of CIP piers. For self-reset piers (Ahmad et al. 2021; Jafarkarimi and Khanmohammadi 2021; Jia et al. 2021b; Mohammad et al. 2021), mixed sliding-rocking (MSR) piers were precast concrete segmental piers with the characteristics of unbonded post-tensioned, end rocking joints and intermediate sliding joints (Fig. 16). MSR columns were developed for buildings in earthquake areas with self-centering, energy consumption and low damage. The research results reflect the trend of the combination of connection structure and energy dissipation structure, which may be a development direction of prefabricated piers in the future.

Fig. 15 The plastic hinge area of bridge pier is modified with CFRP

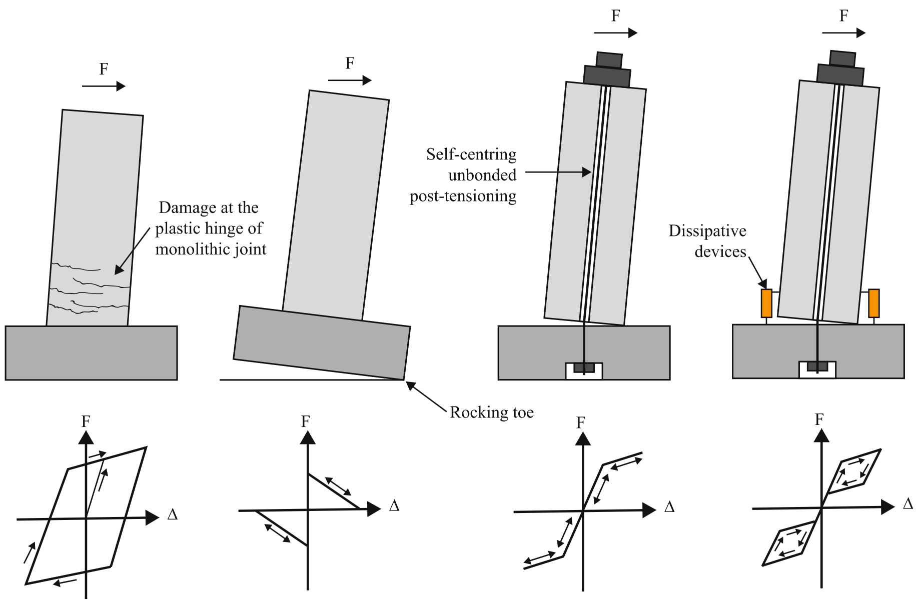

Fig. 16 Schematic diagram of self-reset pier

6.2 Collision and contact problems

6.2.1 Soil-structure interaction

Scholars (Chen 2021; Chen et al. 2021g; Cheshmehkaboodi and Guizani 2021; Chiou 2021; Wen and Limin 2021; Zhang et al. 2021y) have studied the pile-soil interaction under a variety of complex conditions, such as the seismic response and pile-soil interaction under near-fault ground motions. The results show that the soil-structure interaction has an obvious influence on the shear force, bending moment and axial force at the bottom of the pier, which greatly reduces the seismic response of the bridge.

6.2.2 Vehicle-bridge-ground coupling

In the aspect of vehicle-bridge-ground coupling, scholars (Cui and Xu 2021; Lei and Huang 2021; Shamsi et al. 2021; Yu et al. 2021b) have proposed a large number of finite element models, including 3D continuous finite element model (Fig. 17), Chinese CRT-SIItrack system simply supported beam and CRH2 high-speed train coupling model and train-track-bridge-pile group coupling vibration model. The results show that under the earthquake, the existence of the train reduces the response of the pier and bearing, while increases the response of the track structure. Ignoring the train may lead to the most intense response of the vehicle-bridge-ground coupling system.

6.2.3 Pier-water interaction

On the problem of pier-water interaction, scholars (Liang et al. 2021a; Wang et al. 2021c; Zhang et al. 2021b; k; Zhou et al. 2021c) mainly focused on the evaluation of seismic capacity of bridges and the vulnerability analysis of piers and supports; the hydrodynamic additional mass was estimated by the fluid–solid coupling model, and a three-dimensional nonlinear numerical model of the bridge was established. A simplified additional mass formula and a simplified additional model (Fig. 18) were proposed to simulate rectangular hollow piers.

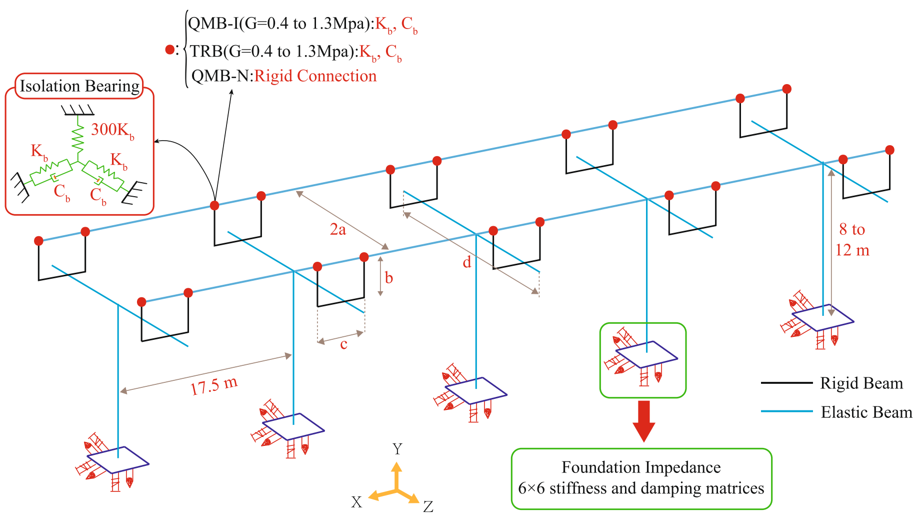

Fig. 17 3D model used for time-history analysis of Bridges based on flexibility

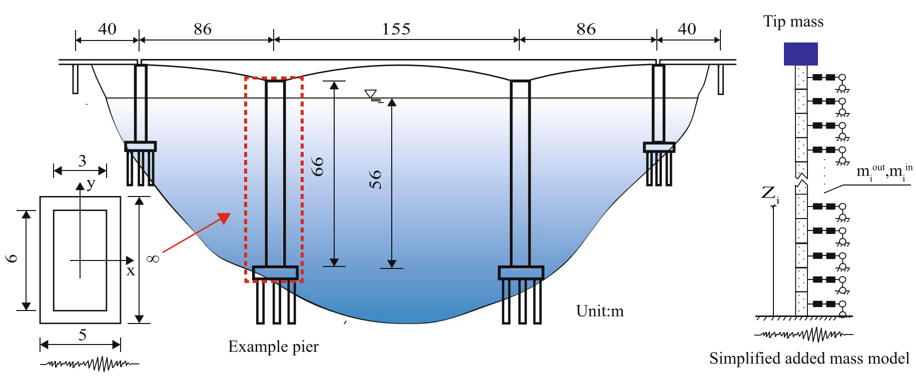

Fig. 18 Example pier and simplified additional mass model

6.2.4 Collision

A large number of studies (Jiao et al. 2021; Oppong et al. 2021) have shown that the interaction of bridge contacts has a great influence on the dynamic characteristics and seismic response of Bridges. However, there are still differences in the calculation results obtained by the interaction models of different contact surfaces, because some simplified contact interaction models will lead to calculation errors. Therefore, to make the response analysis result of bridge structure under various dynamic loads accurate, it is necessary to establish an accurate bridge contact model.

6.3 Seismic isolation technology

6.3.1 Seismic isolation measures

In 2021, scholars (Cao and Liu, 2021; Castaldo and Amendola 2021; Chen and Li 2021; Fang et al. 2022, 2021; He and Unjoh 2022; Ma et al. 2021a; Maghsoudi-Barmi et al. 2021; Song et al. 2021b; Wei et al. 2021a, e; Wen et al. 2021; Zhang et al. 2021a; Zheng et al. 2021c) mainly studied the mechanical properties of new isolation bearings, new structural support systems, isolation devices and so on. Great progress has been made in the research of bridge damping and isolation devices and design methods, and the overall research shows the characteristics of continuous deepening. In terms of damping and isolation devices, many new damping and isolation devices are still to be continuously developed with rubber bearings and viscous dampers as the basic framework, through innovations in materials and structures, continue to enhance the adaptability of seismic isolation devices in different harsh environments to meet the strategic requirements of large tonnage, large deformation and high weather resistance under the strategic background of the transfer of bridge construction to the west.

6.3.2 Design method of damping and isolation system

The research of scholars (Li et al. 2021f; Pang et al. 2021a; Reggiani Manzo et al. 2022) on the design method of seismic isolation system in 2021 was mainly focused on the new seismic system and the performance-based seismic isolation design method. In the aspect of seismic isolation design method, the new design method was innovated constantly, the structure evaluation was more based on the performance, and the parameter design and optimization of the device were more accurate.

6.4 Seismic response and seismic evaluation

6.4.1 Seismic response and vulnerability analysis of bridges

At present, the more mature research methods are shaking table test (Guo et al. 2021b; Wang et al. 2021z) and finite element numerical simulation method (Fayaz and Zareian 2021). Scholars (Dai et al. 2021c; Rachedi et al. 2021; Soleimani and Liu 2022) proposed to use artificial neural network (ANN) to predict the dynamic response of structures under earthquake to overcome the disadvantage for which only a single peak ground acceleration (PGA) parameter is not enough to describe the seismic excitation process. The seismic performance of materials and steel bars of bridge members after performance degradation has been further studied, and a number of scholars (He et al. 2021a; Huang and Yi 2021; Li and Fu 2021) have put forward corresponding analysis models to assess the service life of bridges. At the same time, the bridge uniform damage optimization design process based on intelligent difference algorithm (Fig. 19) is proposed. The anti-seismic problem of near-fault bridge is also the direction that scholars (Wan et al. 2021; Yang et al. 2021c) actively explore in recent years. The bridge structure is more likely to be damaged under the action of acceleration impulse ground motion.

6.4.2 Bridge Seismic system and Evaluation method

The renewal and optimization of bridge seismic system has always been the main research direction of scholars (Guan and Li 2021; Sun et al. 2021b). There is little research on the damping mechanism and damping system of long-span bridges under the action of near-fault and cross-fault and other extreme earthquakes, and the

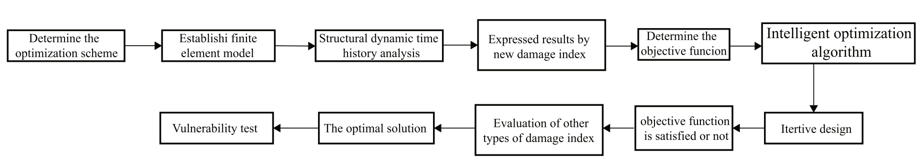

Fig. 19 Flow chart of structural optimization design

relevant damping theory and design methods need to be improved. The overall evaluation method of seismic performance of bridges also had a lot of research results in 2021 (Chen et al. 2021l; Darwash and Mackie 2021; Feng et al. 2021b; Pang et al. 2021b; Safari et al. 2021; Wang et al. 2021k). It was found that the capacity of the bridge system was greatly underestimated by using the simplified model, and the increase of abutment stiffness and strength significantly reduced the displacement and force of the bridge system.

7 Advances in Vibration and Noise Reduction of Rail Transit Bridges

In 2021, great progress was made in the research on vibration reduction and noise reduction of rail transit. This chapter briefly reviews the representative progress including: "the noise source alongside the railway", "research on vibration reduction and noise reduction measures" and "vibration and noise mechanism" of rail transit.

7.1 Noise characteristics research

Clarifying the railway sound source characteristics is the basis of the research on the vibration and noise reduction of high-speed railway. The sound source of high-speed train should be the wheel/rail noise, aerodynamic noise and structure-borne noise. Sheng et al. (2021) and Zhu (2021c) respectively reviewed the research on the wheel/ rail noise and aerodynamic noise.

Structure-borne noise constantly annoys the residents along the rail line and is difficult to eliminate. For steel box girder, Zhang et al. (2021u) elaborated through hammer test study that the setting of the stiffener significantly decreased the structure-borne noise. The influence of the stiffener spacing on the structure-borne noise is greater than that of the thickness of stiffeners. Li et al. (2021a, b, c,d,e,f,g) and Janas (2021) respectively carried out the vibration and acoustic test and found out that the structure-borne noise of steel box girder was broadband distribution, the sound press level peak occurs at 63 to 160 Hz, and the most acoustic radiation contribution was the steel bridge panel. For the large-span steel truss bridge, it's showed in Zhang et al. (2021v) that the structure-borne noise was in the frequency range of 40 ~ 500 Hz.

When the train passes through the bridge section arranged with a sound barrier, the structure-borne noise emerged from the bridge-sound barrier system. Zheng (2021a) established a simulated prediction using a fast multipole boundary element method model for structure-borne noise of a bridge-fully closed sound barrier (FESB) system.

7.2 Research on vibration reduction and noise reduction measures

Noise barrier is the main measure to reduce noise and the acoustic performance of the new-type sound barriers has gained attention. Zheng (2021b) carried out the field test on the FESB considering with various type of sound barriers and sound insulation board of different materials.

To reduce the vibration transmitted to infrastructures under the track, the commonly used measures include the damper fastener and vibration damping rails. Liu et al. (2021f) found that the vibration of the viaduct was affected considering the frequency variation characteristic of the rubber pad of WJ-7B fasteners. Li and Gong (2021) came to conclusion that the rubber float-slab track could effectively reduce the vibration of the large-span steel truss beam bridge; He et al. (2021e) compared the embedded, trapezoidal sleeper and damping pad floating plate track in field test, and results showed that the latter two tracks could better control the vibration of bridge.

Damped rails or restraint damping layers can also be used at typical locations of steel bridges to control vibration and structure-borne noise. Chen et al. (2021k) tested the reconstructed elevated line with damping rail and obtained the noise change during the train passing period; Ou et al. (2021) found that the laying of damping plates had a certain noise reduction effect on steel box girder in the peak frequency band of 200–1000 Hz. Particle damping has been applied to vibration reduction due to its simple structure, wide frequency band and strong environmental adaptability. Jin et al. (2020) applied particle damping to the rail to control the vibration and noise caused by wheel rolling.

According to the pulsating pressure in the speed range of 380–420 km/h in Xiong et al. (2020) and Bi et al. (2021), it can be seen that the pressure on the surface of the sound barrier increases sharply with the increasing train speed. Restricted by the enclosed space, the FESB produce greater aerodynamic pressure. Jing et al. (2021) carried out the wind tunnel test and obtained the aerodynamic pressure distribution in FESB. The above research shows that the peak values of fluctuating wind pressure of the FESB is the largest compared with other types of sound barriers, obviously changes at different sections of the FESB, and are evenly distributed along the circumferential direction of the FESB on the middle section. The impact of aerodynamic pressure will cause severe performance degradation of the sound barrier.

7.3 Study on vibration reduction and noise reduction of periodic structure

Periodic structures often appear in rail transit. The vibration and noise control is correspondingly realized by using the band gap characteristic of elastic wave propagating in periodic medium structure in wave dynamics theory.

For the periodic characteristics of the track structure, Zhao et al. (2021a) proposed a new type of phononic crystal vibration isolator structure placed on the floating plate of the rail damping pad; Jin et al. (2020) designed a vibration isolator by using Bragg scattering and local resonance band gap in the layered honeycomb structure, effectively realizing the ultra wide coupling band gap and achieving the purpose of vibration reduction.

For the infinite periodic Viaduct, Chen et al. (2021e) discussed the dynamic response under different dynamic loads. He et al. (2021f) explored the vibration spectrum of concrete box girders based on the theory of infinite long-period structure. The acoustic radiation characteristics of elastic waves are calculated by the 2.5-dimensional acoustic boundary element method.

In terms of sound barrier research, Qin et al. (2020) proposed three kinds of two-dimensional gas–solid phononic crystal sound barriers, respectively analyzed the energy band structures and determined the noise reduction characteristics of the sound barrier in the band gap rang. Based on phononic crystal and Helmholtz resonator theory, Jiang et al. (2021d) proposed a new type of wind/sound barrier with good noise and aerodynamic pressure reduction effect.

8 Advances in Monitoring and Detection of Steel Bridge

At present, the number of in-service steel bridges with fatigue damage is increasing year by year, but the actual performance requirement of the structure gradually increases, resulting in the deterioration of service performance and the frequent occurrence of accidents such as bridge collapses, which has become a major source of risk for transportation infrastructure. Therefore, for the typical issues of steel bridges in service, such as fatigue cracks, corrosion, loose bolts or fractures, the studies on monitoring and detection are sorted out and summarized, and the current situation, problems, needs and shortcomings are clarified, with a view to providing references for subsequent studies.

8.1 Fatigue cracking monitoring and detection

Fatigue cracking, as one of the most common diseases of steel bridges, is a worldwide problem that limits the safety and durability of steel bridges in service. Fatigue cracking leads to local stress release, so strain-based methods are widely used in monitoring fatigue fragile details of steel bridges (Al-Salih et al. 2021; Mashayekhi et al. 2021; Tochaei et al. 2021). The ultrasonic wave is one of the most common methods of field detection. Shirahata et al. (2021) studied the detection effects of various ultrasonic waves on fatigue crack in welded joint with paint coating. Shrestha et al. (2021) performed an experimental investigation of fatigue in steel with an edge notch using AE to understand source and location of crack formation and growth. Wang (2021b) studied the ultrasonic guided wave detection methods for fatigue cracks in orthotropic steel bridge decks, built an automatic fatigue crack detection system to realize the accurate detection and localization of U-rib and hidden root cracks. With the rapid development of computer technology and artificial intelligence, image recognition technology using computer-aided analysis and visual information processing has become a research hotspot for fatigue crack detection in steel bridges, such as the convolutional neural network Inception-v4 (Zhu et al. 2021b) and the deep learning-based fine crack segmentation network (FCS-Net) (Li et al. 2021g). The magnetization effect occurs in steel under the action of an applied magnetic field or magnetic memory under cyclic loading. When a defect exists on or near the surface of structure, the magnetic field around the location will be distorted and a magnetic leakage field will be formed on the surface, which provides a possibility for monitoring and detection studies based on eddy current and magnetic memory(Ma et al. 2021c; Nguyen and La 2021; Su et al. 2021c).

8.2 Corrosion monitoring and detection

Because the corrosion is usually exposed on the surface of the steel structure, surface corrosion information can be easily obtained by image acquisition methods, researchers have applied deep learning-based image processing methods to steel bridge surface corrosion detection and conducted some exploratory studies. Huang et al. (2021a) and Jin Lim et al. (2021) explored a new corrosion inspection method that combines a deep learning-based fully convolutional neural network U-Net with a newly developed image semantic segmentation model to achieve pixel-level corrosion defect identification of steel bridge. Yang (2021a) proposed a threshold segmentation algorithm based on Hue, Saturation, Value (HSV) chromaticity space for corrosion disease detection. The image was converted to HSV chromaticity space, and the appropriate threshold was selected for disease segmentation and corrosion marking. Some researchers have calculated the damage degree of cables based on the health monitoring data of the cables. Son et al. (2021a) processed multivariate time series and learn temporal correlation based on LSTM (Long Short Term Memory) network to identify abnormal data due to bridge damage or sensor device failure in cable-stayed bridge force health monitoring. Xia et al. (2021) obtained the dynamic response signals at various damage levels, cable forces and cable lengths by analyzing them in the time, frequency, and energy domains. A prediction procedure for cable damage was established using the change rate of wavelet packet total energy (RWE) as the damage index for the cables. Since the magnetic field variability characteristics are highly correlated with the stress and damage on the surface, several scholars have studied the corrosion detection of cables and booms using magnetic detection methods (Ni et al. 2021; Tang et al. 2021b; Zhou et al. 2021a).

8.3 Bolt monitoring and detection

During the operation of a bridge, small vibrations or temperature changes over a long-term period can damage the bolts by loosening, breaking or falling off, seriously threatening the safety of the bridge, pedestrians and vehicles. The looseness of the bolted structure directly affects the vibration characteristics of the structure. Pirdayr et al. (2021) and Wang et al. (2021h) evaluated the looseness of the bolts by the time domain and frequency domain characteristics of the vibration signals, respectively. The impedance-based method inverts the bolt status by measuring the local frequency impedance information of the structure. Na (2021) used PZT to measure the piezoelectric impedance characteristics of different bolt sizes and used probabilistic neural networks for sensing signal feature extraction to achieve rapid identification of bolt loosening status. In the methods based on piezoelectric active sensing, high-frequency excitation can be used to generate ultrasonic-guided waves. When the wave signal passes through the loose part of the bolt, the amplitude, phase and frequency components of the wave will change, according to which the bolt status can be judged (Ding et al. 2022; Pineda Allen and Ng 2021; Quan et al. 2021; Zhang et al. 2021n). Typically, the computer vision-based detection methods use portable devices to capture images, and calculate the bolt rotation angle and screw length based on the two-dimensional information. They have outstanding advantages such as low cost, non-contact measurement, and high visualization, and thus have received a lot of attention from the engineering community. With the development of machine vision, researchers have proposed numerous convolutional neural network models with excellent performance, which have been widely used in bolt disease detection (Huynh 2021; Pan and Yang 2022; Yu et al. 2021d; Yuan et al. 2021a).

9 Advances in Hydrodynamics of Coastal Bridges

Compared to inland bridges, coastal bridges are facing more complicated conditions. Hydrodynamic loadings from hurricane storms, extreme waves and raging currents pose a great threat to the safety of nearshore bridges. In the past year, lots of researchers have devoted to this topic for a deeper understanding of coastal bridge hydrodynamics. To the authors' best knowledge, relevant works can be categorized into three aspects: assessment of wind and wave environment; interactions between extreme waves and coastal bridge superstructures; influences of waves and currents on coastal bridge substructures.

Since wind-generated wave is one of the main mechanisms for inducing extreme waves, a reasonable wind-wave driving model is necessary for the scientific evaluation of environmental loading at bridge site. To this end, comprehensive work was made in 2021 (Shen and Wei 2021; Wu et al. 2021e). Among them, Wu et al. (2021e) established a real-time atmosphere-wave bidirectional coupling model for the South China sea by combining the atmospheric model WRF with the wave model SWAN. According to this model, the spatial–temporal evolution process of typhoon-wave can be predicted with high accuracy. At the same time, considering the correlation among wind, wave and current, some researchers (Jiang et al. 2021b; Li et al. 2021b; Liu et al. 2021e; Ma and Zhang 2022) explored the application of multivariate joint probabilistic functions. Wang and Liu (2021) presented a dynamically coupled approach for simultaneously analyzing storm surges and tsunamis. Then based on an extreme scenario that a storm surge and synthetic tsunami simultaneously happened in the Pearl River Estuary, the differences between linear superposition and fully coupled model were systematically compared. In addition, with the rapid development of artificial intelligence, some machining techniques (Kyprioti et al. 2021; Lee et al. 2021; Meng et al. 2021; Qiao and Myers 2022; Wei 2021) are also employed. Using the geometric prediction method of large storms, Lee et al. (2021) evaluated potential coastal disasters within a region containing tens of thousands of locations. The Kriging's method was employed for geospatial interpolation. In the case of greatly reducing the calculation cost, the accuracy of the hazard curve only exhibited a small deviation.

After investigating numerous coastal bridge damages, a large part of accidents is found to be closely related to the hydrodynamic loadings on bridge superstructures. Yuan et al. (2021b) proposed an effectively pseudo fluid–structure interaction method for investigating the spatial failure mode of coastal bridge superstructures under extreme waves. Two representative failure modes including fall-beam and overturning were discussed in detail. Farvizi et al. (2021) researched the interactions between tsunami waves and skewed box section bridges. Experimental data showed that the skewed bridge deck would suffer additional forces and moment components. Corresponding formulas for predicting tsunami forces on the skewed bridges were also derived. Chen et al. (2021i), Chen et al. (2021j) and Yang et al. (2021e) numerically investigated the responses of various waves impacting on coastal bridge girders like T-girder and box-girder. It is found that the T-girder bridge bears higher and longer-lasting horizontal peak forces than box-girder bridge. Countermeasures for mitigating extreme wave forces on bridge superstructures also attracted some researchers' attention (Gao et al. 2021b; Greco et al. 2021; Qu et al. 2020a). Rajabi et al. (2021) studied the straight floating bridge under homogeneous waves, and found that the wave loadings on joints were reduced by the mooring system. On the other hand, considering homogeneous waves may underestimate the structural response of the large span floating bridge, some studies on inhomogeneous waves and their effects on floating bridges were also conducted (Cheng et al. 2021b; Dai et al. 2021a; b). In terms of wind-wave-bridge coupling systems, Qu et al. (2020b) and Wen et al. (2022) took wind speed, wave height and inundation depth into account, and investigated the hydrodynamic effects of solitary waves, regular waves, and wind for offshore low-profile bridges respectively. Chen and Peng (2021) examined the implications of flow velocity and group pile effects, then proposed an analytical method for short-term pulsation effects on structures. Yu et al. (2021a) investigated the performance of three different time series prediction models (XGBoost, LSTM, ARIMA) in the early warning of structural displacements.

The long-term wave and current impacts also bring about adverse effect on the substructure of coastal bridges, such as piles, caps, and column. Regarding to the pile group foundation, Wang and Qiu (2021) experimentally studied influences of water depth, pile spacing, pile inclination, cap structural type and other factors. It is revealed that the wave force undertaken by the cap even accounts for more than 98% of the total wave force when the water-depth is high. Gao et al. (2021d) numerically analyzed the wave surge on the equilateral triangular cylinders. In the case of estuary tides or inland river floods, waves are usually mild, and current plays a major role. Aghaee-Shalmani and Hakimzadeh (2022) adopted large eddy simulation studying the hydrodynamic characteristics of semi-conical bridge piers with various slope ratios. Results showed that compared to the cylindrical pier, the semi-conical pier could decrease the downstream flow velocity, the bottom shear stress and the vortex dropping frequency simultaneously. In addition, some scholars (Liang et al. 2021b; Tu et al. 2021b; Wang et al. 2021l; Zhang et al. 2022) studied the dynamic response characteristics of bridges under multi-factors including earthquake, wave, deep-water and others. Local scour is another main disease of wading bridges. Yao et al. (2021a) found that the scour depth increased with the diameter of the superstructure. Bor and GÜNey (2021) found that the largest scour pits resulted from rectangular piers among all pier geometries. Baduna Koçyiğit et al. (2021) investigated the effect of submergence depth on the local scour depth of bridges. In scour monitoring and prediction aspect, Zhang et al. (2021h) used an intelligent rock location method combined with an unmanned aerial vehicle to monitor the maximum bridge scour depth. Aly and Erin (2021) found that the straight slot performed the best among the various types of scour mitigation measures.

10 Advances in the Durability of the Concrete Bridge under the Complex Environmental Conditions

The complex environmental conditions (such as temperature, humidity, precipitation, erosion ions, ultraviolet, etc.) can significantly affect the durability of the concrete bridge. This chapter reviews the research related to the durability of the concrete bridge under different environmental conditions in 2021.

10.1 The durability of concrete bridges under corrosion environments

Deterioration of concrete bridge structures in a corrosion environment is the main problem of their serviceability, which may lead to the risk of bridge collapse. This section mainly introduces the durability of the concrete bridge under the ocean and saline soil environments.

10.1.1 Durability research progress of concrete bridges under marine corrosion environment

Coastal bridges exposed to the Marine environment are always eroded by various ions (especially chloride ions and sulfate ions). The erosion process and impact factors of the marine corrosion environment on concrete Bridges are mainly studied through the accelerated corrosion test and exposure test. Hou et al. (2021a) conducted a two-stage corrosion test under a chloride environment on steel fiber concrete components. The deterioration process can be described as local corrosion on the fiber surface and gradually aggravated with the increase of the beam corrosion rate. A continuous load accelerated the steel corrosion due to the rapid reduction of the corrosion potential. In addition, the continuous load and chloride corrosion has an obvious coupling effect. Wei et al. (2021d) investigated the failure mode of the reinforced concrete beam strengthened by CFRP and found that the chloride environmental exposure had a great negative effect on the bending performance of the reinforced concrete beam. In addition, they proposed a theoretical model for predicting the bending strength of the CFRP-reinforced concrete beams. Zhao et al. (2021b) designed four scaled pier specimens and performed cyclic load tests on the specimens after experiencing varying degrees of electro-accelerated corrosion in splash and tidal zones. When the corrosion degree increased, the bearing capacity, ductility, and cumulative energy consumption were reduced. When the corrosion was severe enough, the position of the plastic hinge would be transferred from the bottom of the pier to the corrosion zone. Leng et al. (2021) proposed a new dual time-dependent chloride diffusion model by considering the maximum diffusion phenomenon of concrete structures in the marine environment. Xu et al. (2021d) developed a numerical model that can capture the shear resistance degradation and bending shear coupling behavior of the corrosion column.

10.1.2 Progress on the durability of concrete bridges under saline soil corrosion environment

A large number of harmful ions can be found in saline soil. The multi-factor environment coupling effect can easily cause erosion and deterioration of the concrete structure, which seriously threatens the durability of concrete bridges. Feng et al. (2021d) studied the corrosion damage and bearing characteristics of bridge pile foundations under salt dry–wet-freezing-thaw cycle conditions. To study the seismic flexural strength of reinforced concrete (RC) columns in a saline soil environment, Yan et al. (2021a) designed fourteen inverted T-shaped RC pier columns for electrochemical corrosion tests and repeated loading tests. The research results can provide a reference for the seismic design of columns in the saline soil environment.

10.2 Research Progress of Concrete Bridge under Plateau Environment

For the plateau construction, due to the atmospheric pressure decreasing with the increase of altitude, the bubbles in the concrete are instability, which often reduces the effectiveness of the air-entraining agent (Wang 2021a). In recent years, the durability of concrete in plateau areas has focused on the applicability of the air-entraining agent. He et al. (2021b) studied the mechanism of enhancing the robustness and durability of nano-silica (NS) and the robustness of concrete under low pressure. The adsorption of NS by AEAs on the bubble shell can compact the hydration products of the air pore wall and affect the aperture distribution, thus improving the bending strength and freezing resistance of air-induced concrete at low pressure. Yuan (2021) compared the differences in strength and permeability of concrete in different curing environments, it was found that the compressive strength of concrete under low pressure was higher than that of the same mix proportion under standard pressure.

The large temperature difference and low relative humidity drying can significantly affect the durability of concrete bridges in high-altitude areas. Chen et al. (2021f) investigated the sunshine temperature field characteristics and distribution pattern of a steel–concrete composite beam in a high-altitude area and proposed a solar radiation calculation model under plateau environment. Liu et al. (2021c) investigated the temperature change and temperature effect of thin wall hollow high pier and obtained the temperature field characteristics and displacement distribution rules of thin wall hollow high pier, which can make reasonable suggestions for the design and construction of thin wall hollow high pier in high altitude areas.

10.3 Progress in the durability performance of concrete bridges under extreme high and low-temperature environments

Frozen swelling is one of the main diseases of concrete structures in cold areas. Sun et al. (2022) investigated the influence of frost-swelling damage on the mechanical behavior of the full-size post-tensioned prestressed concrete beam. They established a three-dimensional nonlinear finite element model of the beam to understand the mechanism of the freeze-swelling effect.

In high-temperature conditions, UHPC beams show lower fire resistance than ordinary-strength concrete beams and high-strength concrete beams (Zhu et al. 2021e). To improve the peeling resistance of UHPC at high temperatures, the addition of fibers can delay the development of cracks when the temperature increases, and the mixed steel fiber and synthetic fiber can effectively improve the high-temperature peeling behavior of UHPC (Guo et al. 2021c). Studies have found that polypropylene (PP) fibers can effectively prevent spalling of UHPC under high temperature conditions (Zhang et al. 2021a, b, c, d, e, f, g, h, i, j, k, l, m, n, o, p, q, r, s, t, u, v, w, x, y). At the same time, the addition of iron tailings powder (ITP) particles will delay the peeling of UHPC mortar at high temperatures, and improve the compressive strength and flexural strength of UHPC. Afzal and Khushnood (2021) found that under the condition of high temperature (up to 800℃), high-strength concrete containing carbon nanofibers was found to have better retention in mechanical and physical properties compared to plain concrete.

11 Advances in Bridge Assessment and Reinforcement

Bridges are an important part of infrastructure, and a large number of bridges have been built in China. With the sustained development of China's economy and the steady progress of infrastructure construction, China has become one of the countries with the largest number of bridges in the world. According to the latest statistics of the Ministry of communications (2021), in 2018, the number of highway bridges in China was 851,500, an increase of 19,000 over the previous year, an increase of 2.28% over the previous year; In 2019, the number of highway bridges in China was 878,300, an increase of 26,800 over the previous year, an increase of 3.15% over the previous year, including 5716 super bridges and 108,344 bridges; In 2020, there were 912,800 highway bridges in China, an increase of 34,500 over the previous year, with a year-on-year increase of 3.80%, including 6444 super bridges and 119,935 bridges (2021). Although China's bridge construction industry is flourishing and has a bright future, in the bridge operation stage, a large number of bridges in China will reach their service life ahead of schedule with the increase of the number of vehicles, the increasingly serious problem of vehicle overload, the extended service, the impact of the natural environment, the aging of the structure and other problems. The bearing capacity and service life of these bridges are reduced, and there are huge potential safety hazards. The operation conditions can not meet the needs of transportation, and even cause huge losses (Qin 2000).

In order to reduce the loss of social inherent assets and wealth caused by the premature aging and safety problems of bridges, and ensure the reasonable service life and operation safety of bridges, bridge builders need to spend a lot of human, financial and material resources in the annual inspection, monitoring, evaluation and reinforcement. In order to make more effective use of social resources, more and more better assessment and reinforcement methods have been proposed by scholars. Based on the latest research on bridge evaluation and reinforcement at home and abroad in 2021, this chapter introduces the two aspects of bridge evaluation and bridge reinforcement through systematic sorting, so as to provide reference, application and development for future research and engineering practice.

11.1 Bridge evaluation study

According to previous studies, bridge assessment can be divided into three aspects: bridge health inspection / monitoring, bridge damage identification and bridge structure state assessment. However, the three aspects are closely connected, and an indispensable part of bridge assessment. This section describes the historical development, basic concepts and research progress of each aspect in 2021.

11.1.1 Bridge health inspection

Overview of bridge health inspection At present, bridge health monitoring has experienced nearly 70 years of development. The exploration of bridge health monitoring began in the 1950s. At that time, the concept had been raised and gradually paid attention to. However, due to the backward science and technology at that time, it could not be realized and could only be inspected manually.

With the development of the times, bridge health monitoring not only has new discoveries and new research in monitoring equipment and technology, but also more emphasis has been transferred to the bridge health detection system. The main components of the bridge monitoring system are: data acquisition module, data transmission module, data analysis and processing module, data management module, user interface module, etc. (Luo 2015). Huang et al. (1989) proposed a new method of computer processing for two-dimensional continuous laser monitoring, and a two-dimensional laser monitoring system for displacement of high-rise structures developed to realize the monitoring method.

In general, the research and application of bridge structure health monitoring equipment, technology and system at home and abroad have achieved fruitful research results and gratifying progress.

Progress of health inspection / monitoring technology In the past few years, a large number of bridges have collapsed or failed in the world. Under the background of structural health monitoring, many new detection technologies have been invented. If these new technologies are used properly, it is of great significance to prevent such incidents. Kilic and Caner (2021) combined augmented reality (AR) technology with visual detection, ground penetrating radar (GPR), laser range sensor (LDS), infrared thermal imaging (IRT) and telescope camera (TC), and investigated the defects of a bridge using this method, as shown in Fig. 20. Feroz and Abu Dabous (2021a) comprehensively reviewed the application of UAV and remote sensing technology in bridge condition monitoring. The remote sensing technology integrated with UAV for data acquisition, such as visual image, infrared thermal imaging, lidar and other sensors, was deeply analyzed, and the UAV system based on nondestructive testing was studied in detail.

In the research of long-term monitoring and more efficient monitoring system, Sarwar and Cantero (2021)proposed a new cost-effective bridge health monitoring method for detecting damage under operating conditions. Khandel et al. (2021) proposed a statistical damage detection and location method for evaluating the performance of prestressed concrete bridges using fiber grating sensors. This method uses artificial neural network to establish the relationship between the strain distributions recorded at different sensor positions of the studied beam, and can be applied to long-term monitoring activities under normal traffic load. To sum up, the existing research on bridge detection mainly relies on new equipment. Of course, the optimization of the system and the creation of new concepts have also played a great role in promoting.

11.1.2 Structural damage identification

Overview Structural damage in civil engineering is defined as the reduction of structural safety and durability, which is expressed in structural analysis models as the change of structural physical parameters and boundary conditions. In the 1950s and 1960s, structural damage identification was first widely studied in the field of mechanical engineering due to the need for fault diagnosis of mechanical systems, and fruitful research results were achieved.

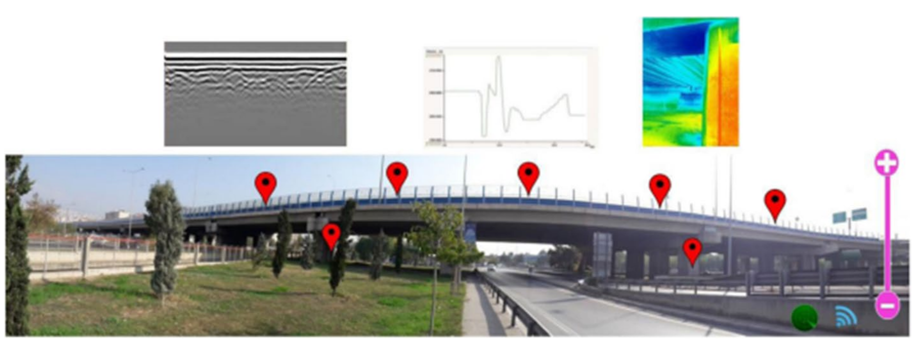

Fig. 20 Augmented reality technology

At the early stage of structural health monitoring development, researchers regarded damage identification as the goal of structural health monitoring and even equated structural damage identification with structural health diagnosis theory. Researchers at home and abroad generally mainly use monitoring acceleration to identify structural damage and modify mechanical models based on dynamic inversion theory. Since structural modal parameters (including frequency, damping ratio, and vibration mode) are functions of structural physical parameters and boundary conditions and are only related to the structure's own characteristics, structural damage identification methods based on modal parameters have been widely studied (Magalhães et al. 2012; Salawu 1997). It also includes such as modal confidence criterion method, curvature modal method, stiffness method, flexibility method, residual force vector method, and modal strain energy method (Farrar et al. 2002). Besides, there exist some methods for data mining of monitoring data to diagnose structural damage by obtaining damage sensitive characteristic monitoring quantities, such as wavelet time–frequency analysis methods (Spanos et al. 2007; Todorovska and Trifunac 2010), neural network intelligent algorithms (Masri et al. 1996; Pnevmatikos and Hatzigeorgiou 2017), fractal nonlinear dynamics methods (Li et al. 2012), blind source separation methods (Yang and Nagarajaiah 2014), etc.

The bridge structure damage monitoring is more of a linkage and carry-over role in bridge health inspection and bridge assessment, based on a large number of data from bridge health inspection, damage monitoring is performed through this data processing method, and the results are fed into bridge assessment for safety and reliability and life assessment.

Research advances In order to study how to apply bridge health monitoring data to identify the damage of key parts of bridges, so as to effectively evaluate the health condition of bridges and solve the problem of poor practicality in the analysis and utilization of bridge structure monitoring data, Yang Shuren et al. (2021) established a strain ratio-based bridge damage periodic online identification and evaluation method, proposed a rapid damage identification of test sections under closed traffic conditions and Ge et al. (2021) explored the role of signal-based nonlinear system identification methods in the rapid post-earthquake damage assessment of reinforced concrete bridge piers, and showed through data analysis comparisons that the Wigner-Ville distribution and Hilbert transform could produce reliable rapid damage detection when the response amplitude was large. The Wigner-Ville distribution has better stability and higher resolution. The introduction of modal filtering and thresholding can significantly improve the stability of the more computationally efficient Hilbert transform.

In terms of identifying damage using deep learning, Son et al. (2021b) identified cables and estimated cable areas of damaged cable-stayed bridges by training a GNN model framework. Simulations were performed using an advanced analysis program (PAAP) to generate tension data of the reduced area cables as required for deep learning training. The efficiency of the method was demonstrated by the data of the cable-stayed bridge generated by PAAP. In summary, damage recognition is more oriented to the processing of monitoring data, so it is believed that machine learning and deep learning, which have newly emerged in recent years, can provide a better research method for structural damage recognition.

11.1.3 Structural condition assessment of bridges

Overview The bridge structural condition assessment is based on the collected bridge technical condition data, using a series of evaluation indicators and evaluation models, to make a judgment on the extent to which the bridge structural condition meets its operational and functional requirements.

The structural condition assessment of bridges can be divided into comprehensive assessment methods and reliability assessment methods, where the conventional comprehensive assessment of bridge structures is based on the application of hierarchical analysis to hierarchize the factors affecting the structural condition of bridges, forming a multi-layer system with several groups of indicators in each layer, first determining the status of each indicator in the bottom layer, and then applying the calculation method of comprehensive assessment to calculate the status of other indicators in each layer. The first comprehensive bridge condition assessment method was developed in the United States in the 1970s, which was used to develop a bridge management system for the daily assessment, management and maintenance decisions of small and medium-sized bridges, and then other developed countries also carried out research and development work in this area. (JTJ073-96) classifies the technical condition of bridges into five classes: Class I, Class II, Class III, Class IV, and Class V. The evaluation criteria for each class of bridge are listed in five items: piers, bearings, superstructure, railing sidewalk, and bearing capacity.

The reliability theory of the structural state of existing bridges was developed along with the theory of reliability assessment of building structures. Foreign research on reliability assessment of existing bridge structures arose in the 1970s during the maintenance and renovation period of developed countries. The research content mainly focuses on damage assessment, mode identification and reliability evaluation of the constructed bridge structures. The research on reliability assessment of constructed structures in China started in the 1980s. In 1987, Yungui Li and academicians Guofan Zhao discussed the differences between in-service structures and proposed structures, proposed methods and procedures for reliability analysis of constructed structures, and discussed reliability assessment and the application of fuzzy mathematics in this field (Zhao 1984).

Progress in safety and life assessment research In the progress of reliability assessment methods, Chen et al. (2021c) proposed a framework for assessing the performance of reinforced concrete bridge piers considering the risk of vehicle collisions. The collision probability under different scenarios was evaluated by considering factors such as the distance from the structural components to the road, the collision angle and the initial velocity. In addition, a probabilistic structural demand and capacity model was developed in the paper considering different damage states during the assessment process, and then the brittleness contours of the studied reinforced concrete bridges were obtained, and the consequences of structural failure under collision were incorporated into the performance assessment process. Wei et al. (2021b) investigated the effect of horizontal ground vibration incidence angle on a high-speed railroad continuous girder bridge (HSRCB) and concluded that in seismic design more attention should be paid to the conclusion of longitudinal seismic damage of sliding layer and CA mortar layer under the action of transverse waves. From the PGA perspective, it was analyzed that longitudinal waves (longitudinal wave = 0) induced seismic response only in the longitudinal direction, while waves in other directions, especially in the transverse direction, induced coupled response in the longitudinal and transverse directions for some components, such as sliding layer and CA mortar layer. In addition, the response of the bridge structural components was more sensitive to the incident angle compared to the track components and the probability of risk was highest when the ground motions fall within horizontal orientations of 67.590 at the bridge longitudinal axis.

In the study of the hierarchical comprehensive assessment method, Yang et al. (2021d) used fuzzy hierarchical analysis to calculate the weights of many indicators affecting the seismic performance assessment of bridges in view of the current situation that there are no norms and standards to follow for the seismic performance assessment of highway bridges in China. A hierarchical and comprehensive assessment method applicable to the seismic performance assessment of highway bridges was proposed, and it was pointed out that this method could screen out bridges with insufficient seismic capacity through quantitative primary assessment of seismic performance, provide a basis for the selection and assessment order of bridges for secondary assessment of seismic performance, and then guide the seismic strengthening of bridge structures.

In a study to accurately predict the performance degradation law of bridges, analyze the performance degradation mechanism of bridge structures with respect to the environment in which the bridges are located, and evaluate bridges from a life cycle perspective, Xu et al. (2021d) conducted an earthquake susceptibility analysis of aging reinforced concrete bridges from a life cycle perspective, considering the damage mode transformation of bridge columns, and proposed that in the whole-life seismic performance evaluation of aging reinforced concrete bridges it was important to consider the potential shear damage of bridge columns. In this paper, a numerical model was developed to reflect the shear load capacity degradation and bending-shear coupling behavior of the corroded columns, and it was verified experimentally that the columns would undergo a damage mode transition due to the effect of corrosion.

In terms of research advances in applying computer techniques and neural networks to bridge assessment, Ni and Chen (2021) developed a SHM-based bridge reliability assessment procedure based on parametric Bayesian mixture modeling. The Markov chain Monte Carlo (MCMC) algorithm combined with Bayesian factors was used to determine the optimal model order and to estimate the joint posterior probability of the hybrid parameters. The conditional reliability index was derived by using a parametric Bayesian mixture model with a first-order reliability method while fully following the Bayesian framework. And the method was used to obtain the estimated value of the reliability index by using the one-year strain monitoring data of the Tsing Ma suspension bridge as an example. In the research progress of structural condition assessment in 2021, many scholars studied it from several perspectives, and machine learning and deep learning, which were hot in recent years, were used in this aspect, distinguishing from the traditional assessment methods.

11.2 Bridge reinforcement research

11.2.1 Bridge Strengthening Overview

The bearing capacity and traffic capacity of bridges is the key to ensuring the smooth flow of roads. With the rapid development of contemporary traffic construction, traffic density and tonnage continue to increase, and the bridge load is increasingly aggravated, many old bridge load-bearing capacity has been unable to meet the new load level requirements, resulting in bridge cracks, bridge aging damage, and other bridge damage. The number of dangerous bridges is increasing year by year, and a considerable number of them are seriously damaged or in overdue operation, which gradually hinder the smooth flow of traffic. Therefore, the strengthening and repairing of bridges has become a key project in the traffic construction of each country. The continuous research and improvement of the strengthening technology of existing bridges not only contributes to the rapid and efficient development of modern transportation, but also brings great safety and economic benefits to the people and the country (Ge et al. 2006; Kuang et al. 2001; Xu et al. 2017; Zeng 2019b).

Existing bridges can have a variety of diseases due to environmental, human and other factors. Common diseases include corrosion of reinforcement, concrete cracks, bearing shear, and pier cracking (Zeng 2019b). In terms of causes, the common diseases of bridge projects can be categorized as improper design and construction (Wang et al. 2006; Wu 2005), environmental and natural factors (Ding 2014), and human factors. The main reinforcement methods for the above diseases are bridge deck reinforcement (Zhang et al. 2020a), increased cross-section reinforcement (Li and Zhu 2013), external prestressing reinforcement, pasting steel plate reinforcement (Hu 2009), additional pile reinforcement (Wang et al. 2011), and pasting carbon fiber sheet reinforcement (Kong and Gong 2021). With the development of technology, the original reinforcement methods also cannot meet the current development concept, and more and more reinforcement techniques are proposed, including new reinforcement materials and new reinforcement concepts.

The following section presents the latest advances in bridge strengthening in 2021 with different components of the bridge structure as research targets, namely strengthening of bridge deck systems, strengthening of main girders and ties (cables), strengthening of bearings, strengthening of piers, strengthening of foundations, and overall strengthening.

11.2.2 Research progress of bridge reinforcement

Bridge deck reinforcement Due to the special supporting conditions, harsh environment and high traffic loads, potholes in bridge decks are very common. Several methods and concepts for bridge deck strengthening were proposed in the 2021 study. Chen et al. (2021b) proposed an interface reinforcement method considering the mechanical response characteristics of the SBDP pothole interface, including a binder layer, a non-woven fabric (NWF) layer, and an ultra-thin asphalt overlay (UTAO). In this paper, the mechanical response of the reinforced SBDP pit interface considering the orthotropic elastic–plastic properties of NWF was elucidated by finite element models (FEMs), and the effectiveness of the technique was evaluated and the theoretical basis for the technique was provided. In addition, the bond performance between NWF and SBDP, the direct crack resistance and fatigue resistance of the interface reinforcement were evaluated by direct tensile test, three-point bending test and fatigue beam test, respectively. It was demonstrated that the innovative method of using NWF layer and UTAO could significantly relieve the horizontal tensile stress state of SBDP pothole interface and make the direct crack resistance and fatigue resistance of the repaired interface much higher. However, from the aspect of improving the stiffness and fatigue performance of conventional OSDs, Feng et al. (2021e) proposed a cost-effective lightweight composite bridge deck (LCBD) system consisting of an orthotropic steel deck (OSD) and lightweight ultra-high performance concrete (UHPC) layers. Four-point bending static and fatigue tests were conducted on two models. It was concluded that increasing the reinforcement rate could increase the flexural stiffness of LCBD and decrease the tensile strain of UHPC plies with relatively small changes. In addition, the flexural strength and reinforcement rate of UHPC were important factors affecting the fatigue life of UHPC layer. When the reinforcement spacing was increased from 40 to 80 mm, the fatigue life of the UHPC layer still met the relevant code requirements. It was also proposed that the existing S–N curve was difficult to be used directly for fatigue life prediction of UHPC layer because the definition of stress level and failure assessment index in fatigue test were very different and need to be modified in further research.

In the finite element research method, Zhang et al. (2021m) established a nonlinear finite element model of ECC connection plate as bridge deck expansion joint cast and tested under monotonic cyclic loading based on experimental data. The results pointed out that the depth-to-span ratio and reinforcement ratio of the connection plate should not exceed 0.12% and 0.72%, and the decoupling length of the connection plate should be greater than 0.8% to obtain a lower bending stiffness. The test results proved that the use of the joint plate reinforced with fiber-reinforced polymer reinforcement was flexible enough to meet the current design requirements.

Main beam and tie reinforcement 2021 research concerning the strengthening of main beams and suspension structures was focused on the use of materials. Zhang et al. (2021l) used a new polyurethane cement composite (PUC) to strengthen a hollow slab bridge and controlled the bending of PUC reinforced concrete reinforced T-beam bridge by the PUC design strength damage mode. The main construction processes, including concrete surface treatment, supporting formwork and casting, were also described in the paper. By conducting load tests before and after the bridge reinforcement, it was concluded that PUC could eliminate bridge loads and improve the stiffness of the hollow slab. The maximum load capacity and stiffness of the main girder were increased by about 20% and 28%, respectively, after casting PUC materials, while the crack width was also reduced to different degrees.

In a more meaningful study on strengthening of old bridges, Heydarinouri et al. (2021) strengthened a 92-year-old riveted railroad bridge in Switzerland using a new retrofit system of prestressed carbon fiber reinforced polymer (CFRP) rods reinforcing the longitudinal beams with double angle steel connections to the floor beams. The reinforcement system transmits forces purely by friction with minimal disturbance to bridge traffic. The system consists of two parts: a newly developed mechanical wedge cylinder anchor for fixing the prestressed CFRP rods and a clamping system for connecting the longitudinal beam flanges. The clamping system reduces the out-of-plane deformation of the connection and thus reduces the stresses in the connection caused by the deformation. Short-term bridge measurements showed that applying a total prestress of 100 kN reduced the major average stresses in the joint hot spots by 47% (from 22.9 MPa to 10.9 MPa) while the stress range remained constant during the passage of passenger trains. Using the modified Wohler curve method (MWCM) as a critical-plane based multi-axial fatigue model, it was observed that the reinforcement system reduced the multi-axial mean stress parameter by 30% under passenger car loading. Long-term monitoring of the reinforcement system using a wireless sensor network (WSN) system showed no loss of prestress in the CFRP rods for seven months since installation.

The authors believe that Heydarinouri's approach is of great significance in the study of similar old bridges, because keeping old bridges standing safely is not only a way to provide continuous traffic convenience, but also a local cultural expression and spiritual support.

Bridge pier reinforcement In the seismic studies, it was shown that many reinforced concrete (RC) bridges were damaged due to excessive residual displacements generated by the bridges after the earthquake, and most of them were due to the damage of the piers, so it also led to the fact that the studies on strengthening of bridge piers were basically on the effects of the earthquake on the piers and how to strengthen the piers to resist the damage of seismic effects.

Most of the studies in the seismic literature in 2021 were conducted with materials, which can be divided into FRP materials and concrete materials, and among the studies using FRP materials, Wang et al. (2021o) used carbon fiber reinforced polymer (CFRP) and polyethylene terephthalate (PET) materials for seismic strengthening of assembled concrete bridge piers, two prefabricated piers with 1/6 size grouted sleeve connections (SFP) and grouted sleeve prestressing tendon composite connections (SSFP) were designed and fabricated, and the damage is shown in Fig. 21. Shake table tests were

(a) Reinforced SFP (b) Reinforced SSFP

Fig. 21 Damage of the reinforced specimens conducted on the model piers. Then, a reinforcement method using CFRP/PET and lateral shift resistant external metal energy dissipators (AS-EMD) was proposed, and the design and implementation of CFRPAS-EMD and PETAS-EMD were established. Zhou et al. (2021f) investigated the seismic strengthening effect of carbon fiber reinforced polymer (CFRP) on circular reinforced concrete (RC) piers under vehicle lateral impact loads. It was also confirmed that the seismic strengthening of circular reinforced concrete piers with carbon fiber fabric could effectively reduce the susceptibility to damage under lateral impact loads and a semi-empirical formula for predicting the maximum displacement under impact loads was derived through tests.

The above scholarly studies all point out that FRP materials will always have good reinforcement effects in seismic strengthening of bridge piers, but Wang et al. (2021w) did not recommend the use of carbon fiber cloth jacketing only for the retrofitting of precast reinforced concrete bridge columns with high corrosion levels, although the premise of not recommending was in corrosive environments, because the retrofitting of bridge columns with high corrosion levels (i.e. 10%) using carbon fiber cloth jacketing could effectively protect the columns from damage in the plastic hinge zone, but the damage mode would shift to fracture of longitudinal reinforcement at the column footing interface, as shown in Fig. 22, leading to an ultimate. The ultimate displacement load capacity was significantly reduced.

Of course, in the research on seismic strengthening of bridge piers, in addition to strengthening structures with FRP materials and evaluating the effectiveness of FRP material strengthening, there are also some studies with other types of concrete materials, such as Ye et al. (2021). To study the seismic damage modes and dynamic response characteristics of rectangular hollow piers of ultra-high performance concrete (UHPC) under dynamic loads, El Centro wave, Taft wave and Northridge wave were selected as seismic excitations for shaking table tests. It is also pointed out that the stiffness of the UHPC rectangular hollow pier decreases after the seismic wave action, but the ultimate bearing capacity does not decrease, and the overall seismic performance is superior, and the reinforcement rate of the UHPC rectangular hollow pier can be reduced appropriately in areas with low seismic intensity. Liu et al. (2021b) proposed a method to improve the energy dissipation capacity of bridge piers by reinforcing them with Crumb Rubber, and the additional damping ratio of the cladding structure was calculated by applying the modal strain energy theory through finite element analysis, and the influence of pier cross-section parameters on the seismic reduction effect was calculated by applying the reaction spectrum method and analyzing the cladding stiffness-damping contribution ratio.

Other studies on bridge piers involved novel bridge seismic systems and post-earthquake damage fatigue. Cai et al. (2021b) investigated a prefabricated segmental bridge

Fig. 22 Damage process at 10% corrosion level

pier PSBC system that used both fiber-reinforced polymer (FRP) reinforcement and steel bars as longitudinal reinforcement for bridge piers, and verified experimentally that the system could increase post-yield stiffness, reduce post-earthquake residual displacement and improve post-yield stiffness and self- centering capacity of the FSR-PSBC system. In summary, bridge pier strengthening involves a wide range of research, from concrete materials, FRP materials and reinforcement materials to seismic systems, and many scholars have pooled their ideas to ensure that bridges can be operated and maintained in a safer way.

Non-pier substructure reinforcement There is little literature about the substructure reinforcement of non-pier, according to the classification of bridge components, it can be divided into cover beam and support reinforcement on piers and foundation and pile reinforcement under piers, in the study of foundation structure reinforcement, Kong et al. (2021) took the fact that the foundation bearing capacity of a 32.5 m span pre-stressed T-beam simply supported girder bridge was insufficient, threatening the safety of bridge operation as the background, and the foundation reinforcement was carried out by anchor static steel pipe pile to make the bridge pier bearing capacity meet the specification requirements. After analysis, the bridge foundation bearing capacity was insufficient because of the early bridge construction on the quality control of the construction of the pile foundation was not enough to produce insufficient pile length and pile diameter, and concrete cavity of pile shaft, and pile head concrete quality was poor, and weak connection with the bearing platform and other diseases. In this paper, strain monitoring and load test were used to verify the results, which showed that the bearing capacity of the steel pipe pile was stabilized and the original foundation load sharing effect was good, which effectively improved the bridge bearing capacity.

Cao et al. (2021). proposed the method of seismic strengthening by using viscous fluid damper (FVD).A continuous girder bridge was used as the background, and the nonlinear time-dynamic analysis method was used to analyze the reinforcement method and parameter selection of FVD. The results showed that the dispersed FVD could control the seismic displacement of the bearing more effectively and had little effect on the seismic internal force of the bridge pier, so it could be used as the seismic strengthening method after the shearing of the bridge bearing, and it was pointed out that the seismic strengthening performance and engineering cost should be compared, and the FVD with smaller damping coefficient and larger velocity index should be selected for seismic strengthening under the premise that the bearing displacement and the internal force of the bridge pier could be controlled. In summary, in the research literature of substructure, there is little research on other structures compared with the number of literature on pier strengthening, and scholars can focus more attention on this aspect in future research.

Others The above classifications can basically be covered in the research literature of 2021, but some of them cannot be classified into the corresponding sections, but they also have great research significance, and in this subsection the authors introduce them in a classified manner. The three main aspects are related to the reinforcement materials of structures, the reinforcement of structures during construction and the design of seismic reinforcement.

In the direction of research about materials, Yang (2021b) studied the application of fiber-reinforced magnesium phosphate cement-based nanocomposites in the rehabilitation and strengthening of bridge structures. The mechanical properties of fiber-reinforced magnesium phosphate cement-based nanocomposites were used to analyze the reinforcement effect of bridge rehabilitation structures under different ballast conditions, which proved that fiber-reinforced magnesium phosphate cement-based nanocomposites could provide good reinforcement for damaged bridge structures. In the area of external prestressing anchorage reinforcement, Fu et al. (2021b) designed two types of anchorage blocks for high-strength weathering steel structures and ultra-high performance concrete (UHPC), and analyzed the feasibility of the two types of external prestressing reinforcement anchorage blocks. The results showed that the stresses and deformations of the two types of anchorage blocks and the stresses in the anchorage zone of the T-beam met the design requirements.

Bridges not only generate the need for reinforcement after the bridge is completed, but also in the construction process, due to the complexity of the construction, some structures in the construction process need to be reinforced and studied (Shi et al. 2021b) as shown in Fig. 23. The finite element software was used to analyze the local instability phenomenon and buckling deformation characteristics of the guide beam, and the stability of the guide beam was studied for four different reinforcement schemes. In terms of seismic strengthening design, Luo et al. (2021a) developed an innovative "quasi-isolated" seismic bridge design method to evaluate the seismic performance of a prototype quasi-isolated highway bridge. The seismic evaluation results verified that the quasi-isolated design strategy was generally effective in preventing global collapse, but the response of a few bridges showed a relatively high risk of bearing debonding and severe pier damage. In summary, although there are few strengthening studies in this vignette, three aspects are covered that can provide guidance for future related studies.

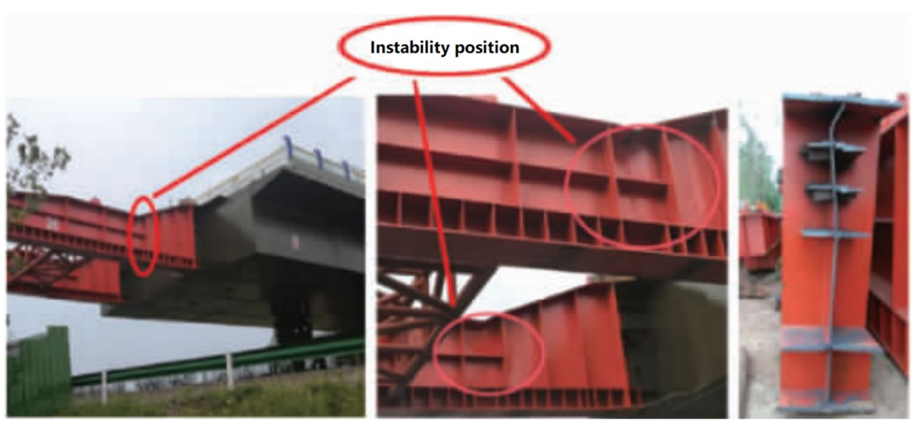

Fig. 23 Instability diagram of guide beam

12 Advances in Technology of Bridge Structure Test

The bridge structure test is a method that aims at obtaining the mechanical behavior of the bridge structure by gauging and analyzing the response of the prototype or model of the structure under the test load. In addition to estimating the actual working performance and bearing capacity to ensure the safe use of the structure, the other considerable task of the bridge structure test is to develop structure calculation theory, assumptions, and methods. In recent years, with the emergence of a round of scientific and technological revolution, the bridge structure test has undergone tremendous changes. In this context, to further grasp the cutting-edge progress, some characteristic achievements in the bridge structure test in 2021 are reviewed and summarized in the following paragraphs, in terms of bridge model test, field test, as well as measuring and test technology of bridge.

12.1 Bridge model test

12.1.1 Static model test

The static model test is one of the most common basic test methods in bridge tests. With the advent of novel materials, structures, and application scenarios, the corresponding model tests are gradually diversified. The representative progress of the static model test in 2021 is as follows. To evaluate the mechanical properties of the prestressed bridge girder prefabricated with Belitic Calcium Sulfoaluminate Cement (BCSA) concrete, Markosian et al. (2021) made a full-scale model and carried out a static model test, for obtaining the compressive strength, tensile strength, static and dynamic elastic modulus, creep, drying, and self-shrinkage.

12.1.2 Dynamic model test

Bridges are often subjected to various dynamic loads, such as earthquake load in service, vehicle load, wind load, waves load, etc. To study the working performance of the structure under dynamic load, it is generally necessary to conduct a dynamic model test. Xu et al. (2021b) proposed a new type of bridge flutter test device, which can avoid the nonlinear factors involved in the traditional free vibration device in the bridge flutter test and thereby ensure the accuracy of large-amplitude vertical-torsional coupled free vibration tests, as shown in Fig. 24. For studying the anti-collision performance of the socket assembled bridge structure without roughness treatment on the connection interface between the precast pier column and the precast foundation, Han et al. (2021b) conducted a model test of four socket assembled and one cast-in-place pier specimens which were subjected to vehicle collision loads. The vehicle collision system is shown in Fig. 25

12.1.3 Fatigue test

Representative progress in the fatigue test includes the following. Zhang et al. (2021x) designed an accelerated corrosion test and fatigue test to study the corrosion performance of weathering steel and high-performance steel and the fatigue performance under the high corrosion environment. Yoshitake et al. (2021) conducted a test on a cantilever reinforced concrete slab specimen embedded with high modulus carbon fiber

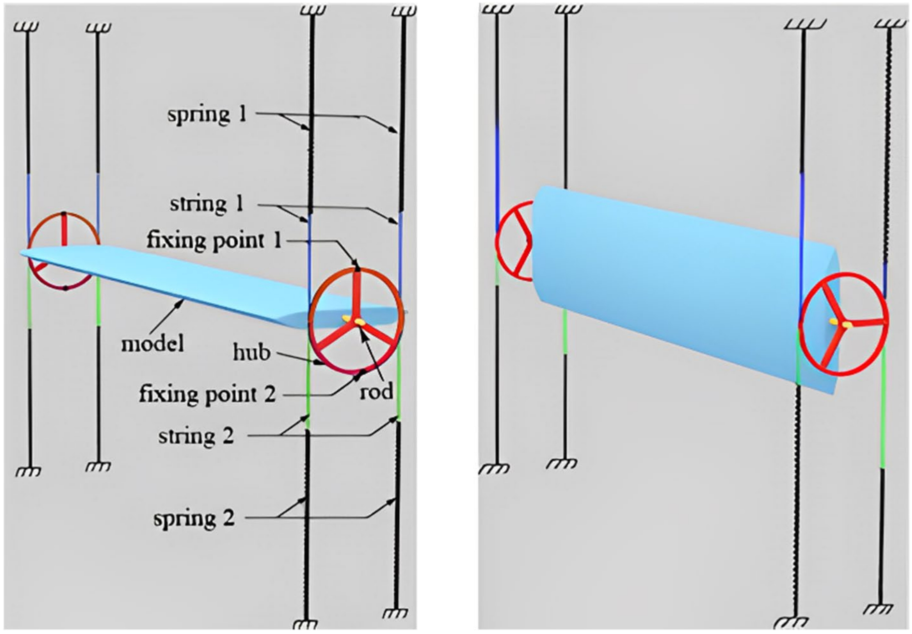

Fig. 24 Schematic diagram of the new device: **a** rotation angle = 0° **b** rotation angle = 90°

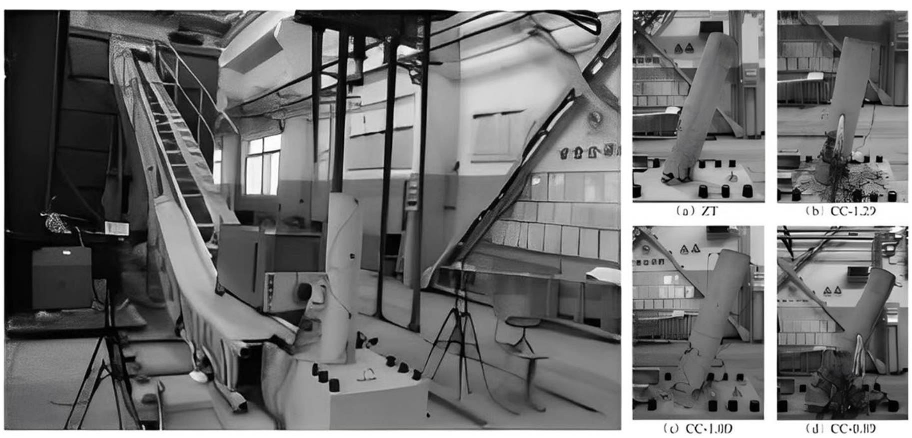

Fig. 25 Dynamic model test of socket assembled pier under vehicle collision

reinforced polymer (CFRP) rods using a moving-wheel fatigue tester to study the fatigue durability of the cantilever bridge deck strengthened with high modulus CFRP.

12.1.4 Other model tests

In order to study the fire temperature field of prestressed concrete box girder coated with fire retardant coating and the stiffness degradation performance after the fire, Hou et al. (2021b) carried out fire model test research on three simple supported box girders with and without expansion type fire retardant coating. The structure was subjected to fire on three sides, i.e. the bottom plate and webs on both sides. As shown in Fig. 26, the test beam was loaded at two points. During the test, the concentrated load on the box beam was maintained at 40% of the normal service load.

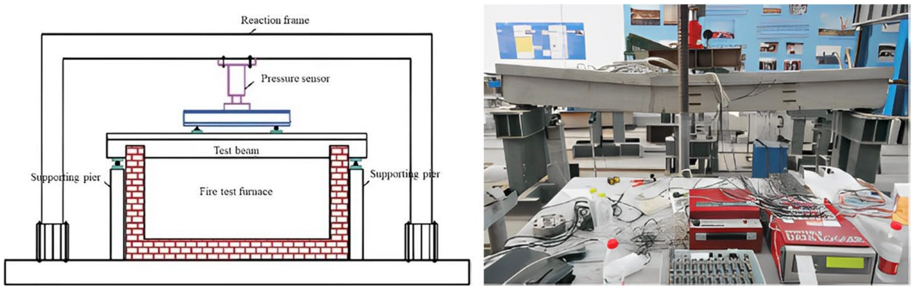

Fig. 26 The fire model test (left) and static load test (right) of simply supported box girder with intumescent fire retardant coating

12.2 Bridge field test

The bridge field test is a means to test the actual working state of the bridge directly. Pimentel et al. (2021) developed a cost-effective bridge dynamic weighing (B-WIM) system, which can identify the train load through optical fiber technology and estimate the train speed, geometric structure, and static axle load, as shown in Fig. 27. The field test of the system adopted the technology of considering fixed reference points and moving measurement points, including the use of high-sensitivity piezoelectric accelerometers. The structural response of the train passing at different speeds verified the function and accuracy of the B-WIM system.

12.3 Measuring and testing technology of bridge

Bridge detection generally includes geometric displacement measurement, stress–strain measurement, acceleration measurement, structural frequency measurement, concrete crack, and structural crack detection, etc. With the development of equipment and data processing technology, the bridge detection technology based on machine vision and data-driven method made good progress in 2021, which will be reviewed in detail next.

In terms of geometric displacement measurement, Gaxiola-Camacho et al. (2021) proposed a probabilistic risk extraction method combining GPS technology and structural dynamic displacement. Lydon et al. (2021) proposed a mobile camera technology to capture the displacement response of a bridge model under live load to identify the bridge damage.

In terms of stress and strain measurement, Mashayekhi et al. (2021) developed a data-driven fatigue assessment platform for welded components of steel bridges. Based on

Fig. 27 The bridge dynamic weighing system

the 12-month stress cycle data of a vertical lifting truss bridge, the damage detection and positioning were carried out. Cao et al. (2022) proposed a method for mutual inspection of damage between bridges in the same cluster by using the difference ratio of predicted strain monitoring data under time-varying ambient temperature.

In terms of the frequency test of structures, to overcome the limitations of the traditional-based methods, such as the long time interval between two tests and the influence of different environmental conditions, Zhu and Zhang (2021) proposed a rapid detection method based on structural frequency attenuation. Specifically, for damaged concrete bridges, vehicles passing across the damaged area of the bridge will lead to the opening of partial concrete cracks which are closed without vehicle loads. That is, damage detection can be realized by identifying breathing cracks induced frequency decay.

In terms of concrete crack and structural crack detection, Dan and Dan (2021) proposed an automatic identification technology of bridge surface crack suitable for mobile machine vision detection. By using two-dimensional amplitude and phase estimation methods, high-precision two-dimensional spectrum estimation crack images were obtained, and then low-frequency information was filtered and crack information was marked to realize automatic identification of crack target images. Yan et al. (2021b) combined the RGB image with the LIDAR data collected by the UAV, automatically extracted the target area from the image by identifying the target worthy of attention in the LIDAR data, and retrieved the depth information to estimate the actual pixel size of concrete cracks, which was convenient for the detection and quantification of concrete cracks, as shown in Fig. 28

13 Advances in Intelligent Construction and Safe Operation and Maintenance of Bridges

There are a large number of bridges in China. The traditional structure detection and operation and maintenance methods are no longer applicable. The construction, detection, evaluation, and prediction based on artificial intelligence methods are the key to realizing the integration of structural intelligent diagnosis and treatment. Multi source heterogeneous data fusion algorithm, digital twin technology, bridge life cycle structure evaluation and long-term performance evolution prediction and analysis theory have become the important contents of domestic and foreign scholars.

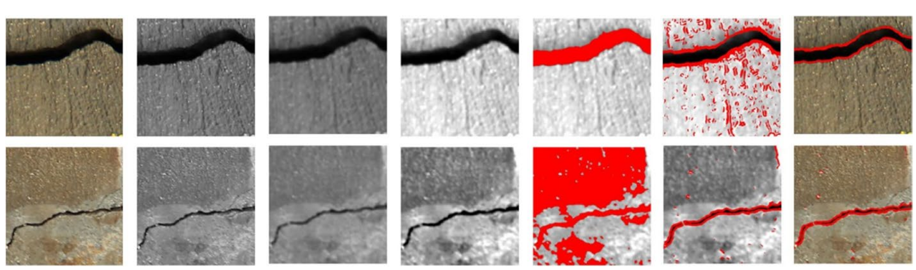

Fig. 28 Crack pixels of the identified crack block

13.1 Intelligent design and construction of bridges

This section mainly conducts literature research and analysis on the intelligent design and construction optimization methods of bridges based on machine learning.

Machine learning provides an important theoretical basis for bridge intelligent design. The application of Genetic Algorithm (GA), Swarm Intelligence Algorithm (SIA), Artificial Neural Network (ANN) and other algorithms greatly improve the efficiency and quality of bridge design optimization. Based on GA, Korus et al. (2021) established a visual planning genetic algorithm framework through visual programming language to realize the automation of the optimization process of arch bridge geometric parameters. Nour et al. (2021) proposed an optimization method for the section size of T-shaped beam and the arrangement of prestressing tendon with the total design cost as the objective function. SIA realizes the optimization of targets by simulating the behavior of biological groups. Based on the artificial SIA, Tang et al. (2021a) and Jawad et al. (2021) respectively proposed the local stiffness optimization method of finite element model of bridge structure and the combined optimization algorithm of plane and space truss structure size. ANN realizes the processing of target information by simulating the brain's processing and memory of information. Serwa et al. (2021) developed a software applying neural network and proposed a semi-automatic three-dimensional registration method for laser scanning data of bridge structure ground. A single machine learning algorithm often has some shortcomings. For example, although genetic algorithm has strong global search ability, its local search ability is not ideal. Therefore, when applying machine learning algorithms, it often combines two or more algorithms or interacts with other technical means to make up for the shortcomings of a single algorithm (Qin et al. 2021b).

13.2 Bridge intelligent detection and operation and maintenance decision

For the management and maintenance of bridges, scholars focus on the four aspects of intelligent detection, intelligent identification, intelligent assessment, intelligent early warning and intelligent maintenance.

13.2.1 Bridge intelligent detection technology

In terms of non-contact detection technology, Yu et al. (2021c) proposed two long-span bridge deflection remote detection methods based on flexible vision. Abedin et al. (2021) proposed a health monitoring technology for steel box girder bridges based on non-contact sensors. Qin et al. (2021a, b) developed an InSAR integration method of structural knowledge, and proposed a synthetic aperture radar interferometry integration method of structural knowledge for high-precision deformation monitoring and risk identification of cross sea bridges.

In terms of UAV(unmanned aerial vehicle) detection technology, Peng et al. (2021) proposed a crack recognition method combining R-FCN (region-based fully convolutional network) and Haar AdaBoost, which is suitable for UAV image recognition, based on the machine vision of UAV. Feroz and Abu Dabous (2021b) proposed a remote sensing application method for bridge condition assessment based on UAV. Since the crack images collected by the UAV under the moving shooting condition have quality defects such as low definition, complex background and serious interference of light and noise, Dan (2021) proposed a method for automatic recognition of bridge surface cracks based on 2D-APES (two-dimensional amplitude and phase estimation) and mobile machine vision.

The application of Convolutional Neural Network (CNN) enables UAV to accurately locate the crack position. However, UAV images are greatly affected by climate and environment. How to accurately analyze UAV images and realize positioning is still a research topic.

Aiming at the problems of low accuracy and efficiency of bridge crack detection in the actual scene, Wu et al. (2021d) proposed a crack detection algorithm based on a convolutional neural network and conditional random field (CRF). Ma et al. (2021d) designed and developed an unmanned aerial vehicle patrol system composed of two subsystems of data acquisition and processing. The system can detect millimeter level cracks and is of great significance to the bridge maintenance stage. Han et al. (2021a) proposed an intelligent detection robot integrating ultrasonic detection and image recognition based on convolution neural network algorithm to solve the problem of low efficiency of conventional nondestructive testing methods, which provides a new method for detecting cracks on the deck of orthotropic steel bridge deck. The intelligent monitoring robot is shown in Fig. 29.

13.2.2 Intelligent recognition algorithm

This section summarizes the research on bridge dynamic signal identification, bridge apparent disease identification, bridge structure damage identification, potential fire risk bridge identification and early warning.

In terms of bridge dynamic signal identification, Liu et al. (2021j) proposed a method for identifying the target position and frequency of beam vibration based on CA-CFAR, which can be used for bridge vibration detection and identification, determining the position with large amplitude of the bridge body and detecting the vibration frequency of the position.

In terms of bridge apparent disease identification, in view of the characteristics of complex shape, uneven distribution and different sizes of the apparent diseases of reinforced concrete bridges under complex environment, Zou et al. (2021a) proposed a structural apparent multi disease identification method based on improved YOLO v3, which can quickly and accurately detect structural diseases. Aiming at the problems of low efficiency and low accuracy of steel bridge disease identification, Zhu et al. (2021b) proposed a method of steel structure apparent disease identification based on

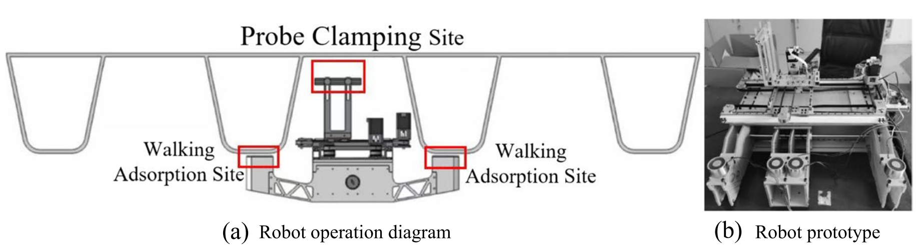

Fig. 29 Intelligent inspection robot

convolution neural network and transfer learning. The recognition results of images containing cracks determine the recognition efficiency and integrity of structural cracks. Therefore, Ma (2021) improved the mask algorithm and proposed a measurement algorithm based on skeleton images.

In the direction of bridge structure damage identification, Bao et al. (2021) constructed a damage identification program based on BP neural network algorithm. Shao et al. (2021a) obtained low-level acceleration signals based on Newmark method and python. By training convolutional self coding neural network, they can accurately find the time when structural damage occurs. Nguyen (2021) proposed a brand-new energy consumption coefficient to identify and evaluate the state of the structure, and used Kelvin Voigt model to improve the traditional Hooke's linear mechanical change model to truly simulate the properties of the structure under actual working conditions; In addition, in order to make the new parameters play a more accurate role in the recognition process, the paper uses the amplitude acceleration data of the structure to train on the deep learning platform.

From the perspective of bridge fire risk, Abedi and Naser (2021) established a comprehensive database based on the data collected from international bridge fire events, and used machine learning, deep learning and genetic algorithm to train, built a model with the ability to identify existing, new and historical bridges damaged by fire or with collapse tendency caused by fire, and proposed a fast autonomous and intelligent machine learning methods (rapid, automated, and intelligent, RAI).

13.2.3 Intelligent assessment and prediction

Aiming at the intelligent evaluation and prediction of bridges, scholars at home and abroad have carried out in-depth research on the performance of bridges from the aspects of deformation, dynamic response, fatigue performance, structural life prediction and evaluation, bridge performance, damage evaluation and seismic performance by using various algorithms and models such as machine learning algorithm, deep learning network and Markov chain Monte Carlo simulation.

In terms of deformation evaluation and prediction of bridge structure state, Gou et al. (2021c) constructed a general analytical model of bridge track deformation mapping, which provides theoretical support for intelligent evaluation of high-speed railway. Wang et al. (2021y) established a bridge deformation prediction model driven by big data based on track geometry detection, and proposed a new method for railway bridge deformation evaluation. Wang et al. (2021u) established a prediction model database through Latin hypercube sampling and finite element model, and proposed a deflection prediction framework of neural network based on mental evolutionary computation (MEC) algorithm and back propagation (BP) algorithm.

In terms of bridge dynamic response analysis and prediction, Li et al. (2021a) proposed a method framework for vehicle bridge system dynamic response prediction based on feedforward neural network (FFNN) and long short-term memory (LSTM) network. Gou et al. (2021a, b) proposed a joint probability distribution model of wind and rain based on the mixed copula function based on the long-term meteorological monitoring data of Lanzhou Xinjiang high speed railway, and constructed a wind speed early warning system using the artificial neural network model.

In terms of the evaluation and prediction of the fatigue evolution and service life of the bridge life cycle, Jiang et al. (2021a) proposed a digital twin driving framework for the prediction of the fatigue start-up life and residual life of the steel bridge by establishing a probabilistic multi-scale model of the fatigue evolution of the bridge life cycle. Zhu and Wang (2021, 2021a,b,c,d,e,f) established a new deterioration prediction model of bridges (DPMB) combining recurrent neural network (RNN) and CNN.

13.2.4 Intelligent maintenance

With the continuous growth of the number of bridge construction and service life, the bridge gradually transits from the rapid construction stage to the operation and maintenance management stage. Based on the bridge intelligent detection technology, the intelligent identification algorithm model is built to carry out intelligent evaluation and prediction of the structure, and finally a scientific evaluation system and a life-cycle evaluation model based on informatization are established (He et al. 2021d), so as to realize the intelligent maintenance and repair of the bridge throughout its life cycle.

Li et al. (2021d) proposed a named entity recognition (NER) neural model based on etymology to enhance machine reading comprehension, which was used to recognize planar and nested entities in Chinese Bridge Inspection texts. Cheng et al. (2021a) adopted the new concept of invisible computer and developed a decision support system for bridge life cycle management in terms of safety assessment and disaster prevention, which can realize the safety assessment and disaster warning in the bridge operation and maintenance stage. Samadi et al. (2021) developed an integrated framework based on Bridge Information Model (BrIM) and bridge maintenance optimization. BrIM can automatically feed back to the developed GA optimization system, and use the visualization function of BrIM to assist decision-making. Abdelmaksoud et al. (2021) proposed a probabilistic framework for bridge patrol inspection and maintenance scheduling based on a parametric logistics model. Hadjidemetriou et al. (2022) regarded the bridge network as a multi system multi component network (MSMCN), and proposed a heterogeneous bridge network prediction group maintenance priority method based on bridge conditions and network criticality, which can solve the maintenance priority problem of bridges in the road network. GUI et al. (2021b) studied a multi parameter project level bridge maintenance decision algorithm based on probabilistic neural network method, radial basis function method and principal component analysis method, and proposed a comprehensive evaluation model for project level bridge maintenance decision. Nili et al. (2021) combined GA and discrete event simulation (DES) and proposed a simulated bridge maintenance optimization (SiBMO) framework, which can optimize the bridge maintenance plan and determine the best sequence of the maintenance process, so as to minimize the maintenance cost.

14 Conclusions and Prospects

The paper reviews some advances in bridge engineering in 2021, including concrete bridges and its high performance materials, steel bridge, composite girders, bridge seismic resistance, vibration and noise reduction of rail transit bridges, monitoring and detection of steel bridge, hydrodynamics of coastal bridges, the durability of the concrete bridge under the complex environmental conditions, cable-supported bridge analysis theories, bridge assessment and reinforcement, technology of bridge structure test, and intelligent construction and safe operation and maintenance of bridges. Conclusions and prospects for these aspects are listed as follow.

14.1 Concrete Bridges and its High Performance Materials

According to the above research progress, the following conclusions and suggestions are obtained. (1) In the research of concrete bridges, the research of single methods and factors has become mature. Using the mixed simulation method of finite element and discrete element to realize the high-precision analysis of the overall and local performance of concrete bridges and to explore the operation and maintenance scheme of bridges under the coupling of multiple factors are the hot spots that should be paid attention to in the future. (2) In terms of high-performance concrete materials for bridges, the existing research is mainly based on mechanical properties. The research on the workability, durability and structural application of fiber reinforced concrete, the strength development mechanism and maintenance system of GPC, and the large-scale and standardized application development of UHPC still need further attention. (3) In terms of high-performance reinforcement research, it is suggested that in-depth research can be carried out on the bonding performance of FRP with different types and different surface forms under special circumstances, as well as the performance of steel-FRP composite reinforced members. In general, the future development of concrete bridges will follow the direction of diversified analysis methods and high-performance materials (especially high toughness and green energy conservation).

14.2 Steel Bridge

Some large-scale and characteristic steel bridges built at home and abroad in 2021, such as the 1915 Canakkale Bridge, the Chibi Yangtze River Highway Bridge, the Zangmu Bridge crossing the Yarlung Zangbo River, the Pi River Bridge, the New El Felden Railway Bridge in Egypt, and the Hanjiangwan Bridge in Wuhan, have been successfully completed and opened to traffic and many major technological advances have been made. Many new advances have been made in the research of new and special materials and components of steel bridges, such as steel for high heat input welding, weathering steel and high performance steel, and welding materials for high toughness bridge weathering steel, orthotropic steel bridge decks for annealing treatment after welding and non-destructive testing of weld fatigue cracking of steel decks, with better performance.

14.3 Composite Girders

As for shear connectors, basic shear performance and the coupling effects of mechanical behavior and complex environments are mentioned. The researches on high strength bolts connectors are more than before, and the applicability is verified. However, the disadvantages of high-strength bolts, such as brittle fracture, loss of preloading force, should be further studied, when under long-term use. Many improved connectors are applied and the short-term performance is studied. As for steel–concrete composite bridges, researches on the eccentric effects of prestressing tendon, the arrangement of studs and bars are focused more. The application of new materials and prestressing tendon is still the common treatment on the mechanical behavior under negative moments. The superiority of high-performance concrete is extensively verified by push-out tests and bridge-type tests. Multiple types of loads and coupling effects of the environments are paid more attention, such as cyclic loads, extreme temperature, corrosion and long-term loads. The studies on composite box girders with corrugated webs are more than other bridge types.

14.4 Cable-Supported Bridge Analysis Theories

Conventional design methods for connecting components of cable-supported bridges are simple and empirical, thus their mechanical performances in practice may not be fully recognized or utilized. The above investigations in 2021 indicate that analysis of connecting components based on the nonlinear theories has been conducted. However, it is still insufficient to construct a systematic ultimate limit state design method for various connecting components. Related research needs to be further carried out.

14.5 Bridge Seismic Resistance

The research progress in the seismic field of bridges in 2021 is systematically combed. The conclusions are as follows. (1) For the traditional integral pouring RC pier, the researchers mainly discuss the influence of various factors on its seismic performance by means of experiment and numerical simulation. The connection method of prefabricated pier is improved to become a structural member with low damage and self-reset. (2) The contact interaction of the bridge has a great influence on the dynamic characteristics and seismic response of the bridge. Some simplified contact interactions are often used in the finite element simulation, which will lead to calculation errors. (3) In terms of damping and isolation devices, many new damping and isolation devices are still continuously developed with rubber bearings and viscous dampers as the basic framework. In terms of seismic isolation design methods, new design methods are constantly innovated, and structural evaluation is more based on performance. (4) Artificial intelligence technology has also been more widely used in bridge seismic design and analysis, such as directly predicting the seismic response of bridges. The great potential of artificial intelligence technology in civil engineering will be further explored in the future.

14.6 Vibration and Noise Reduction of Rail Transit Bridges

(1) Identification and prediction of sound sources of high-speed rail. The study of high-speed rail sound source is the basis of vibration and noise reduction. With the speed increase of high-speed rail, the train sound sources are more mixed and miscellaneous, so the research on sound source identification and accurate prediction is still necessary. (2) Vibration and noise control strategy of high-speed rail / rail transit structure system. In the rail transit, the vibration and noise problem of the structural system such as viaduct, bridge-sound barrier and bridge construction integration is prominent, and the research on the vibration and noise control strategy still needs to be deepened. (3) Study on the vibration and noise mechanism of periodic structure along rail traffic. In the future, different forms of periodic structure in rail transit should be studied from the micro level to expand the band gap characteristics of elastic wave propagation.

14.7 Monitoring and Detection of Steel Bridge

The traditional manual detection methods are inefficient and difficult to meet the high precision and efficiency requirements of bridge detection. With the rapid development of sensing technology, computer technology, signal processing, artificial intelligence, and big data, the monitoring and detection of steel bridge diseases has a new development opportunity. The following stage of study will concentrate on the creation of new intelligent monitoring and detection key technologies and equipment, followed by the construction of a steel bridge disease identification, location, and intelligent sensing system.

14.8 Hydrodynamics of Coastal Bridges

In summary, current research mainly focus on the interactions between various waves and existing coastal bridge forms. At the same time, there are also some researchers proposing effective countermeasures for mitigating hydrodynamic loads on coastal bridges. Nevertheless, much more work remains to be done and only a few cautious prospects are given here. (1) Further research on the coupling analytical model of multiple environmental factors. (2) Practical devices for reducing extreme wave loadings on existing coastal bridges. (3) Safety early warning system for coastal bridges that suffer severe hydrodynamic forces.

14.9 The Durability of the Concrete Bridge under the Complex Environmental Conditions

From the research on the durability of the concrete bridge in the complex environment in 2021, it can be seen that the investigations related to the durability of the concrete bridge under different environmental coupling effects and extreme environments of has made certain progress. Combined with the current needs of traffic construction and development, the authors suggest that the research can be conducted from the following aspects: (1) The action mechanism and coupling mechanism of various environmental factors on the durability of concrete bridges need to be systematically studied and verified; (2) It is necessary to carry out the field test research on the components and structures of concrete bridges. (3) It is necessary to establish the material structure integration theoretical framework of a complex environment and concrete bridge durability for establishing the relationship between material durability and structural service performance.

14.10 Bridge Assessment and Reinforcement

It can be found from the current retrieved literature that the research on bridge evaluation and reinforcement by domestic and foreign scholars has gone deep into all aspects, from the health monitoring when the bridge is established, to the damage identification based on the monitoring data, to the research on the evaluation system and the reinforcement of the various components and the whole bridge. However, the authors believe that some research directions can be more in-depth and some urgent problems need to be solved. It mainly includes the following aspects: (1) The bridge reinforcement and evaluation method based on computer application can apply the machine learning and deep learning in the computer to the evaluation, make the monitoring data processing more scientific and efficient, and make the evaluation method more effective; (2) Protection and reinforcement treatment of the upper and lower connecting parts of the bridge; (3) Research on fatigue seismic reinforcement of bridge piers in the ocean, acid and alkali environment.

14.11 Technology of Bridge Structure Test

From the above investigation, it can be seen that the bridge test is progressing in the direction of interdisciplinary intersection, among which the model test still keeps a developing trend, mainly in the diversification of test sites, the innovation and upgrading of loading and measuring equipment, and the application of new test methods. In addition, measuring and testing technology is one of the hot research fields of bridge testing. The non-contact detection method based on machine vision, the automation and intelligence of detection technology, and the measurement data processing method based on artificial intelligence and big data technology are the current research hotspots.

14.12 Intelligent Construction and Safe Operation and Maintenance of Bridges

(1) In the aspect of bridge intelligent design, based on the existing research results of bridge intelligent design, further research should deepen the application of various intelligent algorithms in model modification and optimization, and put forward the theory and method of adaptive bridge intelligent design based on machine learning; In the aspect of intelligent construction, an efficient fusion algorithm of multi-source heterogeneous data in the bridge construction scene is constructed, and the digital twin theory of intelligent construction is proposed, forming a new construction technology of deep integration of material, structure and information technology. (2) In the aspect of bridge intelligent detection and operation and maintenance decision-making, research and development of intelligent detection robots are proposed to be carried out, and a dynamic detection system where reliable operations are used to maintain detection equipment in complex environments is also proposed to be developed. The intelligent diagnosis and treatment data set of structure is constructed, the intelligent recognition algorithm of structural surface defects is studied, and the intelligent information processing and intelligent detection theory based on deep learning are established. (3) In the aspect of bridge life cycle performance evaluation and performance evolution prediction, the time series database and relational database within the whole life cycle of the structure are established, the dynamic digital mapping method of the bridge is proposed, and the algorithm of bridge life cycle performance evaluation and prediction is established. Focusing on the three major demands of "safety, intelligence and green", through the interdisciplinary integration, integrating the artificial intelligence method and the bridge life cycle concept, it is expected to achieve a breakthrough in the four-dimensional (space & time) life cycle design theory, further develop the twin platform of bridge intelligent construction and safe operation, promote the transformation and upgrading of the bridge industry, and finally realize the "industrialization, digitization and intellectualization" of Chinese bridges.

Bridges are being built worldwide as the need for infrastructure and transportation systems grows. For example, in the construction of the Sichuan-Tibet Railway, the relative height difference from the Sichuan Basin to the Qinghai-Tibet Plateau is over 3000 m. The collision and extrusion of plates lead to earthquakes, which leads to serious hidden danger to bridge structure safety. Along the line belongs to the alpine climate, day and night temperature difference is significant, ultraviolet light is strong, and the bridge structure materials also have high requirements. At the same time, the deep canyon in this area makes construction difficult. Another example is the Canakkale Bridge, Shiziyang Bridge, and other super-span Bridges across the sea and river. The whole bridge should bear not only the effect of wind load but also the effect of wave load on its foundation. The damage of such super-span Bridges is huge. No matter whether it is the bridge in a dangerous mountainous area or a bridge across river and sea, the research on its structure life guarantee and intelligent disaster prevention and reduction is still not sufficient. Therefore, new materials, artificial intelligence, computer technology, and other aspects are the development direction of global bridge engineering to achieve breakthroughs.

Abbreviations

ANN	Artificial neural network
AR	Augmented reality
BCSA	Belitic Calcium Sulfoaluminate Cement
CA	Cement asphalt
CFRP	Carbon fiber reinforced polymer
CRH	China railway highspeed
CRTS	China Railway Track System
ECC	Engineering cement composite
FEMs	Finite element models
FRP	Fiber reinforced polymer
GNN	Graph neural networks
GPR	Ground penetrating radar
HSR	Hybrid sliding-rocking
HSRCB	High-speed railroad continuous girder bridge
IRT	Nfrared thermal imaging
LCBD	Lightweight composite bridge deck
LDS	Laser range sensor
MCMC	Markov chain monte carlo
MWCM	Modified Wohler curve method
NWF	Nonwoven fabric
OSD	Orthotropic anisotropic steel deck
PAAP	Practical advanced analysis program
PET	Polyethylene terephthalate
PGA	Peak ground acceleration
PUC	Polyurethane cement
RC	Reinforced concrete
TC	Telescope camera
UAV	Unmanned aerial vehicle
UHPC	Ultra-high performance concrete
UTAO	Ultra-thin asphalt overlay
WSN	Wireless sensor network

Acknowledgements
We also need to acknowledge the following people for their positive contributions, which are listed as follow.
Chapter 1: Renda Zhao, Chenggong Zhao.
Chapter 2: Kaifeng Zheng.
Chapter 3: Xing Wei, Zongyi Wen.
Chapter 4: Ruili Shen, Lunhua Bai.
Chapter 5: Hongyu Jia, Sijie Chen, Caizhi Sun, Canhui Zhao, Shixiong Zheng.
Chapter 6: Xiaozhen Li, Jing Zheng, Ran Bi, Hao Luo, Derui Kong, Xun Zhang.
Chapter 7: Qinghua Zhang, Chuang Cui.
Chapter 8: Guoji Xu.
Chapter 9: Yulin Zhan, Ruizhe Si, Yamei Zang, Zhilun Li, Wenfeng Huang, Yuehan Sun.
Chapter 10: Fang Zhang, Jiechao Deng.
Chapter 11: Qianhui Pu, Yu Hong, Hanyu Wang.
Chapter 12: Hongye Gou, Zhuang Tan, Zhenqian Su, Hairong Ren, Fei Hu, Xiao Hu, Hao Gao, Jin Fu.
Coordinator:Chuanjin Yu, Peng He.

Authors' contributions

This paper is the result of the joint efforts of dozens of teachers in the Department of Bridge Engineering. The authors have only compiled their contributions for peer reference. All authors have read and approved the manuscript. Only some major contributors are listed as follows: Renda Zhao, Kaifeng Zheng, Xing Wei, Hongyu Jia, Xiaozhen Li, Qinghua Zhang, Guoji Xu, Yulin Zhan, Ruili Shen, Fang Zhang, Qianhui Pu, Hongye Gou and Chuanjin Yu. We are very grateful to all the authors who contributed to the article.

Funding

The authors are grateful for the financial supports by the National Natural Science Foundation of China (51778531, 51 778533, 51878561, 51978579, 52108176, 52278220, 51878564), The Transportation Science and Technology Project of Sichuan Province (2020-B-02, 2019-ZL-12), Innovation driven development project(GUIKE AA21077011-4), and Sichuan Science and Technology Program (2021JDTD0012).

Availability of data and materials

Not applicable.

Declarations

Competing interests

The authors declare that they have no competing interests. Author Qianhui Pu is a member of the Editorial Board for Advances in Bridge Engineering.

Received: 25 September 2022 Accepted: 27 October 2022
Published online: 30 December 2022

References

Abedin M, Mehrabi AB (2021) Health monitoring of steel box girder bridges using non-contact sensors. Structures, 4012–4024.

Abdelmaksoud AM, Balomenos GP, Becker TC (2021) Parameterized logistic models for bridge inspection and maintenance scheduling. J Bridg Eng 26(10):04021072

Abdollahnia H, Alizadeh Elizei MH, Reza Kashyzadeh K (2021) Multiaxial Fatigue Life Assessment of Integral Concrete Bridge with a Real-Scale and Complicated Geometry Due to the Simultaneous Effects of Temperature Variations and Sea Waves Clash. Journal of Marine Science and Engineering 9(12):1433

Abedi M, Naser MZ (2021) RAI: Rapid, Autonomous and Intelligent machine learning approach to identify fire-vulnerable bridges. Appl Soft Comput 113:107896

Aboukifa M, Moustafa MA (2021) Experimental seismic behavior of ultra-high performance concrete columns with high strength steel reinforcement. Eng Struct 232:111885

Afzal MT, Khushnood RA (2021) Influence of carbon nano fibers (CNF) on the performance of high strength concrete exposed to elevated temperatures. Constr Build Mater 268:121108

Aghaee-Shalmani Y, Hakimzadeh H (2022) Large eddy simulation of flow around semi-conical piers vertically mounted on the bed. Environ Fluid Mechanics. 22(5):1211–32

Ahmad, R., A. M. Shahria, and T. Robert. (2021) Experimental Investigations on the Lateral Cyclic Response of Post-Tensioned Rocking Steel Bridge Piers. J Struct Eng. 147 (12).

Ahmed T, Elchalakani M, Karrech A, Ali MM, Guo L (2021) Development of ECO-UHPC with very-low-C3A cement and ground granulated blast-furnace slag. Constr Build Mater 284:04021211

AL-Hawarneh, M., and M. S. Alam. (2021) Lateral Cyclic Response of RC Bridge Piers Made of Recycled Concrete: Experimental Study. J Bridg Eng 26(5):04021018

Al-Salih H, Juno M, Collins W, Bennett C, Li J (2021) Application of a digital image correlation bridge inspection methodology on geometrically complex bifurcated distortion-induced fatigue cracking. Fatigue Fract Eng Mater Struct 44(11):3186–3201

Alsharari F, El-Zohairy A, Salim H, El-Sisi AE-D (2021a) Numerical investigation of the monotonic behavior of strengthened Steel-Concrete composite girders. Eng Struct 246:113081

Alsharari F, El-Zohairy A, Salim H, El-Sisi A (2021b) Pre-damage effect on the residual behavior of externally post-tensioned fatigued steel-concrete composite beams. Structures 32:578–587

Aly AM, Dougherty E (2021) Bridge pier geometry effects on local scour potential: A comparative study. Ocean Eng 234:109326

Amirchoupani P, Abdollahzadeh G, Hamidi H (2021) Improvement of energy damage index bounds for circular reinforced concrete bridge piers under dynamic analysis. Struct Concr 22(6):3315–3335

Arévalo D, Hernández L, Gómez C, Velasteguí G, Guaminga E, Baquero R, Dibujés R (2021) Structural performance of steel angle shear connectors with different orientation. Case Studies in Construction Materials 14:e00523

Aslı BOR, M. Ş. GÜNEY. (2021) Experimental Investigation of Scour Hole Characteristics for Different Shapes of Piers Caused by Flood Hydrograph Succeeding Steady Flow. Teknik Dergi 10739(10766):611

Ataei A, Zeynalian M (2021) A study on structural performance of deconstructable bolted shear connectors in composite beams. Structures. 29:519–533 (Elsevier)

Baduna Koçyiğit M, Karakurt O, Akay H (2021) Effect of various flow, sediment and geometrical parameters on partially or fully submerged deck scour. SN Applied Sciences 3(3):1–17

Bai L, Shen R, Yan Q, Wang L, Miao R, Zhao Y (2021) Progressive-models method for evaluating interactive stability of steel box girders for bridges–Extension of progressive collapse method in ship structures. Elsevier, pp 3848–3861

Bao L, Cao Y, Zhao N, Meng X, Zhang X (2021) Application of BP Neural Network and Curvature Mode Theory in Bridge Damage Identification. J Shenyang Jianzhu Univ (Natural Sci) 37(2):296–302
Benjumea J, Saiidi M, Itani A (2021) Biaxial Seismic Performance of a Two-Span Concrete Bridge Model with Six ABC Connections. J Bridg Eng 26(8):04021056
Benyahi K, Bouafia Y, Oudjene M, Barboura S, Kachi MS (2021) Numerical Procedure for the Three-Dimensional Nonlinear Modelling of Composite Steel-Concrete Beams. Int J Steel Struct 21(3):1063–1081
Bi R, Li X, Zheng J, Hu Z, Li S. (2021) Fluctuating Wind Pressure Characteristics of Vertical Sound Barrier on 400 km · h-1 High-Speed Railway Bridge. China Railway Sci 42(6):68–77
Biswas RK, Iwanami M, Chijiwa N, Nakayama K (2021) Numerical evaluation on the effect of steel bar corrosion on the cyclic behaviour of RC bridge piers. Mater Today Proc 44:2393–2398
Cai L, Fang J, Fan L (2021a) Experiment study on the push-out shear group studs in precast prefabricated composite beams. Science Technology and Engineering 21(23):9947–9953
Cai Z, Yuan W, Wang Z, Smith ST (2021b) Seismic behavior of precast segmental bridge columns reinforced with hybrid FRP-steel bars. Eng Struct 228:111484
Cao F, Liu C (2021) Utilization of FVDs for Seismic Strengthening of Bridge Bearings. Bridge Construction 51(1):95–100
Cao H, Chen Y, Li J, Liu S (2021) Static characteristics analysis of three-tower suspension bridges with central buckle using a simplified model. Eng Struct 245:112916
Cao J, Liu Y, Li C (2022) Damage cross detection between bridges monitored within one cluster using the difference ratio of projected strain monitoring data. Struct Health Monit 21(2):571–595
Castaldo P, Amendola G (2021) Optimal DCFP bearing properties and seismic performance assessment in nondimensional form for isolated bridges. Earthquake Eng Struct Dynam 50(9):2442–2461
Chen X, Li C (2021) Seismic assessment of tall pier bridges with double-column bents retrofitted with buckling restrained braces subjected to near-fault motions. Eng Struct 226:111390
Chen L, Liu G, Zhang X, Pan G (2021b) An innovative interface reinforcement method for steel bridge deck pavement pothole repair. Constr Build Mater 298:123838
Chen L, Qian J, Tu B, Frangopol DM, Dong Y (2021c) Performance-based risk assessment of reinforced concrete bridge piers subjected to vehicle collision. Eng Struct 229:111640
Chen L, Sun W, Chen B, Shi Z, Lai J, Feng J (2021d) Multiscale study of fibre orientation effect on pullout and tensile behavior of steel fibre reinforced concrete. Constr Build Mater 283:122506
Chen L-L, Lu J-F, Feng Q-S (2021e) A coupled model for a moving mass and the periodic viaduct subjected to seismic waves. Arch Appl Mech 91(6):2761–2780
Chen S, Su Y, Ban X, Shi L (2021f) Study on Solar Radiation Temperature Field of Steel-concrete Composite Girder in High Altitude Area. Railw Eng 61(4):12–16
Chen S, Wu R, Zhang J, Gu Y (2021g) Topography and soil-structure interaction effects on the seismic response of three-dimensional canyon-crossing bridge. Chinese Journal of Theoretical and Applied Mechanics 53(6):1781–1794
Chen X, Xu W, Lin C, Sun H, Zeng X, Liu Q, Chen S (2021j) A comparative study on wave-deck interactions of T-type and box girder decks under regular waves. Ocean Eng 231:109067
Chen Y, Feng Q, Luo K, Xin W, Luo X (2021k) Noise characteristics of urban rail transit viaduct installing damping rail. J Traffic Transp Eng 21:169–178
Chen Z, Zheng S, Ding Z, Zhang J, Tai Y-J (2021l) Seismic reliability evaluation of bridges under spatially varying ground motions using a four-parameter distribution. Eng Struct 247:113157
Chen Y, Peng W (2021) Time history analysis method for the combined action of extreme fluctuating wind and wave on the maximum double cantilever structure of rigid frame bridge considering the influence of flow velocity. IOP Conference Series: Earth and Environmental Science. IOP Publishing, p 012113
Chen J, Zhang H, Yu Q-Q (2021a) Monotonic and fatigue behavior of steel-concrete composite beams subjected to corrosion. Structures. 34:1973–1984 (Elsevier)
Chen S, Zhao H, Li J, Zhu Z. (2021h) Time-dependent reliability analysis of reinforced concrete bridge under atmospheric environment. Chin J Comput Mechanics 1–8.
Chen X, Xu G, Lin C, Sun H, Zeng X, Chen Z (2021i) A comparative study on lateral displacements of movable T-deck and Box-deck under solitary waves. Structures 34:1614–1635 (Elsevier)
Chen. (2021) Seismic Performance of Tall Pier Bridges Considering Soil-Structure-Interactions. J Tongji Univ (Natural Sci), 49 (6).
Cheng M, Fang Y, Chiu Y, Wu Y, Lin T (2021a) Design and Maintenance Information Integration for Concrete Bridge Assessment and Disaster Prevention. J Perform Constr Facil 35(3):04021015
Cheng Z, Svangstu E, Moan T, Gao Z (2021b) Assessment of inhomogeneity in environmental conditions in a Norwegian fjord for design of floating bridges. Ocean Eng 220:108474
Cheng Z, Zhang Q, Bao Y, Deng P, Wei C, Li M (2021c) Flexural behavior of corrugated steel-UHPC composite bridge decks. Eng Struct 246:113066
Cheshmehkaboodi N, Guizani L (2021) On the influence of earthquakes and soil characteristics on seismic response and performance of isolated bridges. Arab J Geosci 14(5):1–12
Chiniforush AA, Ataei A, Bradford MA (2021) Experimental study of deconstructable bolt shear connectors subjected to cyclic loading. J Constr Steel Res 183:106741
Chiou (2021) Numerical investigation of seismic performance of bridge piers with spread footings considering pier plastic hinging and footing rocking, sliding, and settlement. Eng Struct 245:112821
Crossing Continents (2022) Crossing Continents, the Longest Mid-Span Suspension Bridge in the World
Cui C, Xu Y (2021) Mechanism study of vehicle-bridge dynamic interaction under earthquake ground motion. Earthquake Eng Struct Dynam 50(7):1931–1947
Dai J, Leira BJ, Moan T, Alsos HS (2021a) Effect of wave inhomogeneity on fatigue damage of mooring lines of a side-anchored floating bridge. Ocean Eng 219:108304
Dai J, Stefanakos C, Leira BJ, Alsos HS (2021b) Effect of modelling inhomogeneous wave conditions on structural responses of a very long floating bridge. Journal of Marine Science and Engineering 9(5):548

Dai L, Zhang W, Tian S (2021c) Convolutional neural network estimation of bridge linear elastic seismic response. Earthquake Engineering and Engineering Dynamics 41(4):188–195
Dan D, Dan Q (2021) Automatic recognition of surface cracks in bridges based on 2D-APES and mobile machine vision. Measurement 168:108429
Daou A, Mahayri AR, Daou Y, Baalbaki O, Khatib M (2021) The Use of Shear Connectors for Enhancing the Performance of Steel-Concrete Composite Beams: Experimental and Numerical Assessment. International Journal of Steel Structures 21(6):1966–1976
Darwash HH, Mackie KR (2021) Effect of seat-type abutment load path and failure mode on seismic response of straight ordinary bridges. Eng Struct 242:112560
Deng W, Liu D, Peng Z, Zhang J (2021) Behavior of Cantilever Composite Girder Bridges with CSWs under Eccentric Loading. KSCE J Civ Eng 25(10):3925–3939
Ding Y (2014) Strengthening technology of bridges and its application. China Construction 9:164–165
Ding J, Zhu J, Kang J, Wang X (2021a) Experimental study on grouped stud shear connectors in precast steel-UHPC composite bridge. Eng Struct 242:112479
Ding Y, Wu D, Su J, Li Z-X, Zong L, Feng K (2021b) Experimental and numerical investigations on seismic performance of RC bridge piers considering buckling and low-cycle fatigue of high-strength steel bars. Eng Struct 227:111464
Ding J, Wang H, Yuan B, Sun W, Sun Q, Ma Q (2022) Ultrasonic guided wave bolt preload identification based on the fusion of energy entropy and support vector machine. Comput Integr Manuf Syst 28(4):1001–1010
Dong J, Chen Y, Wu Q, Hu A, Jiang R, Wang C, Tong Z, Song H, Xu T (2021) Research on flexural behavior of composite box continuous girder with corrugated steel webs and trusses. Adv Struct Eng 24(15):3580–3593
Du W, Che P, Wu J, Li Y (2021) Welding technology of high performance bridge steel Q690qE. Welding Technology 50(6):24–28
Du H, Hu X, Shi D, Xue W (2022) Flexural Performance of Composite Beams Using High-Strength Steel and High-Strength Concrete. International Journal of Steel Structures 22(1):27–41
Duan L, Wang C, Zhai M, Wang S, Si H (2020) Monitoringand evaluation of fatigue damage for orthotropic steel deck usingacoustic. Journal of Traffic and Transportation Engineering 20(1):60–73
El-Khier MA, Morcous G (2021) Precast concrete deck-to-girder connection using Ultra-High Performance Concrete (UHPC) shear pockets. Eng Struct 248:113082
Fan D, Yu R, Shui Z, Liu K, Feng Y, Wang S, Li K, Tan J, He Y (2021a) A new development of eco-friendly Ultra-High performance concrete (UHPC): Towards efficient steel slag application and multi-objective optimization. Constr Build Mater 306:124913
Fan J-S, Liu Y-F, Liu C (2021b) Experiment study and refined modeling of temperature field of steel-concrete composite beam bridges. Eng Struct 240:112350
Fang C, Liang D, Zheng Y, Lu S (2022) Seismic performance of bridges with novel SMA cable-restrained high damping rubber bearings against near-fault ground motions. Earthquake Eng Struct Dynam 51(1):44–65
Fang R, Kang L, Zhang W. (2021) Seismic reduction and isolation mechanism and tests for self-reset and friction energy-dissipating pedestal. J Vibration Shoc 40(23):83–90.
Farrar CR, Czarnecki JJ, Sohn H, Hemez FM. (2002) A review of structural health monitoring literature 1996–2001. Data Acquisition la-13976-m.
Farvizi F, Melville BW, Shamseldin AY, Shafiei S, Hendi E (2021) Experimental investigation of tsunami bore-induced forces and pressures on skewed box section bridges. Ocean Eng 224:108730
Fayaz J, Zareian F (2021) An efficient algorithm to simulate site-based ground motions that match a target spectrum. Earthquake Eng Struct Dynam 50(13):3532–3549
Feng J, Yin G, Tuo H, Wen C, Liu Z, Liang J, Zhang Y (2021a) Uniaxial compressive behavior of hook-end steel and macro-polypropylene hybrid fibers reinforced recycled aggregate concrete. Constr Build Mater 304:124559
Feng R, Yuan W, Sextos A (2021b) Probabilistic loss assessment of curved bridges considering the effect of ground motion directionality. Earthquake Eng Struct Dynam 50(13):3623–3645
Feng W, Feng H, Zhou Z, Shi X (2021c) Analysis of the Shear Capacity of Ultrahigh Performance Concrete Beams Based on the Modified Compression Field Theory. Adv Mater Sci Eng 2021:1–15
Feng Z, Huo J, Hu H, Zhao R, Wang F, Jiang G, Yao X, Li T, Song Z (2021d) Research on corrosion damage and bearing characteristics of bridge pile foundation concrete under a dry-wet-freeze-thaw cycle. Advances in Civil Engineering 2021(6):1–13
Feng Z, Li C, He J, Ke L, Lei Z, Vasdravellis G (2021e) Static and fatigue test on lightweight UHPC-OSD composite bridge deck system subjected to hogging moment. Eng Struct 241:112459
Feng X, Zheng K, Heng J, Zhu J, He X (2022) Fatigue performance of rib-to-deck joints in orthotropic steel deck with PWHT. J Construct Steel Res 196:107420 Elsevier
Feroz S, Abu Dabous S (2021b) Uav-based remote sensing applications for bridge condition assessment. Remote Sensing 13(9):1809
Feroz S, Abu Dabous S (2021a) Uav-based remote sensing applications for bridge condition assessment. Remote Sensing 13(9):1809 (Multidisciplinary Digital Publishing Institute)
Fu J, Wan S, Yang Y, Su Q, Han W, Zhu Y (2021a) Accelerated corrosion behavior of weathering steel Q345qDNH for bridge in industrial atmosphere. Constr Build Mater 306:124864
Fu X, Hu C, Gao H (2021b) Research on Anchoring External Prestressing Tendons with Wedges in Long-Span T Beam Strengthening. World Bridges 49(1):101–106
Gao D, Gu Z, Wei C, Wu C, Pang Y (2021a) Effects of fiber clustering on fatigue behavior of steel fiber reinforced concrete beams. Constr Build Mater 301:124070
Gao H, Song Y, Fang Q, Li S (2021b) Wave forces on box-girder-type bridge deck located behind trench or breakwater. Ocean Eng 237:109618
Gao Y, Li C, Wang X, Zhou Z, Fan L, Heng J (2021c) Shear-slip behaviour of prefabricated composite shear stud connectors in composite bridges. Eng Struct 240:112148

Gao Y, Zhu J, Qu X, Wang L, Wang B (2021d) Numerical simulation of wave run-up on three cylinders in an equilateral-triangular arrangement. Ocean Eng 233:109176
Gara F, Carbonari S, Leoni G, Dezi L (2021) Finite Elements for Higher Order Steel-Concrete Composite Beams. Appl Sci 11(2):568
Gaxiola-Camacho JR, Vazquez-Ontiveros JR, Guzman-Acevedo GM, Bennett RA, Reyes-Blanco JM, Vazquez-Becerra GE (2021) Real-Time Probabilistic Structural Evaluation of Bridges Using Dynamic Displacements Extracted via GPS Technology. J Surv Eng 147(2):04021002
Ge K, Niu B, Ma L, Yin N (2006) Analysis on the Applicability of CFRP in Bridge Strengthening Engineering. China Railway Science 27(4):51–56
Ge X, Alexander NA, Kashani MM (2021) Rapid post-earthquake damage assessment of ageing reinforced concrete bridge piers using time-frequency analysis. Struct Infrastruct Eng 17(9):1228–1244
Gou H, Chen X, Bao Y (2021a) A wind hazard warning system for safe and efficient operation of high-speed trains. Autom Constr 132:103952
Gou H, Leng D, Wang H, Pu Q (2021b) Joint probability distribution model of wind velocity and rainfall with mixed Copula function. China Journal of Highway and Transport 34(2):309
Gou H, Yang B, Liu Y, Pu Q (2021c) Deformation mapping relationship and running safety evaluation of train-track-bridge system for high-speed railway in complex conditions. China Journal of Highway and Transport 34(4):162
Greco F, Lonetti P, Blasi PN (2021) Impact mitigation measures for bridges under extreme flood actions. J Fluids Struct 106:103381
Gu J, Gu L (2017) Application of large energy welding steel from design perspective. Mar Technol 3:76–80
Guan Z, Li J (2021) Advances in earthquake resisting systems for long-span bridges. Scientia Sinica (Technologica) 51(5):493–504
Gui C, Lei J, Lin W, Xia C, Duan Z (2021a) Static Performance and Elastic Buckling Analysis of Stiffened Plates with Flat Flanges. International Journal of Steel Structures 21(5):1588–1604
Gui C, Zhang J, Lei J, Hou Y, Zhang Y, Qian Z (2021b) A comprehensive evaluation algorithm for project-level bridge maintenance decision-making. J Clean Prod 289:125713
Guo H, Wei H, Yang D, Liu Y, Wang Z, Tian J (2021a) Experimental research on fatigue performance of Q690 high strength steel in marine corrosive environment. Chin Civil Eng J 54(5):36–45
Guo W, Li J, Guan Z (2021b) Shake table test on a long-span cable-stayed bridge with viscous dampers considering wave passage effects. J Bridg Eng 26(2):04020118
Guo Z, Zhuang C, Li Z, Chen Y (2021c) Mechanical properties of carbon fiber reinforced concrete (CFRC) after exposure to high temperatures. Compos Struct 256:113072
Hadi MN, Ali S, Sheikh MN (2021) Experimental Study of GFRP-Reinforced Geopolymer Concrete Columns under Different Loading Conditions. J Compos Constr 25:04021052
Hadjidemetriou GM, Herrera M, Parlikad AK (2022) Condition and criticality-based predictive maintenance prioritisation for networks of bridges. Struct Infrastruct Eng 18(8):1207–1221
Hamid WK, Steinberg EP, Khoury I, Semendary AA, Walsh K (2021) Thermally Induced Behavior of Paired Internally Cured Concrete and Conventional Concrete Decks in Composite Bridges. J Bridg Eng 26(4):04021016
Han B, Gou H, Hua H, Wang J, M. yang, and Y. Liang. (2021a) Research on intelligent detection robot for fatigue crack of OSD. Highway 66(11):143–148
Han Y, Wang L, Liu Z (2021b) Model experimental analysis on the dynamic response of a socket prefabricated pier under vehicle collision. J Vibration Shock 40(22):267–274+288
Hassan RF, Al-Salim NH, Mohammed NS, Hussein HH (2022) Experimental study and theoretical prediction on torsional strength with different steel fiber reinforced concretes and Cross-Section areas. Eng Struct 251:113559
Hassanin AI, Shabaan HF, Elsheikh AI (2021) Cyclic loading behavior on strengthened composite beams using external post-tensioning tendons (experimental study). Structures 29:1119–1136 (Elsevier)
He X, Unjoh S (2022) Development of rocking isolation bearing system (RIBS) to control excessive seismic responses of bridge structures. Earthquake Eng Struct Dynam 51(2):369–392
He H, Huang L, Wu S, Ding J (2021a) Uniform Damage Oriented Seismic Optimal Analysis of Continuous Rigid Frame Bridges with Unequal High Piers. Journal of Basic Science and Engineering 29(6):1461–1473
He R, Yang Z, Gan VJ, Chen H, Cao D (2021b) Mechanism of nano-silica to enhance the robustness and durability of concrete in low air pressure for sustainable civil infrastructures. J Clean Prod 321:128783
He S, Guan P, Wang Q, Fang Z, Mosallam A (2021c) Investigation on structural performance of perfobond strip connector group in steel-concrete joints. Eng Struct 242:112571
He S, Wang A, Zhu Z, Zhao Y (2021d) Research Progress on Intelligent Detection Technologies of Highway Bridges. China Journal of Highway and Transport 34(12):12
He W, He K, Zou C, Yu Y (2021e) Experimental noise and vibration characteristics of elevated urban rail transit considering the effect of track structures and noise barriers. Environ Sci Pollut Res 28(33):45903–45919
He Y, Cheng G, Han J, Sheng X (2021f) Modeling noise radiation from concrete box girder bridges as an infinitely long periodic structure excited by a high-speed train. J Vibration Acoustics 143(3):031015
He Z-Q, Li Y, Xu T, Liu Z, Ma ZJ (2021g) Crack-based serviceability assessment of post-tensioned segmental concrete box-girder bridges. Structures 30:1097–1108
Heydarinouri H, Nussbaumer A, Motavalli M, Ghafoori E (2021) Strengthening of steel connections in a 92-year-old railway bridge using prestressed CFRP rods: Multiaxial fatigue design criterion. J Bridge Eng 26(6):04021023
Hosseini SM, Mashiri F, Mirza O (2021) Parametric study of innovative bolted shear connectors using 3D finite element modelling. J Constr Steel Res 179:106565
Hou L, Peng Y, Xu R, Zhang X, Huang T, Chen D (2021a) Corrosion behavior and flexural performance of reinforced SFRC beams under sustained loading and chloride attack. Eng Struct 242:112553
Hou W, Zhang G, Li Y, Hu W (2021b) Experimental Study on Temperature Field and Stiffness Degradation of PC Box Girder Considering Fire-retardant Coating. China Journal of Highway and Transport 34(6):57–68

Hu W (2009) Selection and application of reinforcement methods for old and dangerous bridges. Scientific and Technological Innovation 3:246
Hu Y, Qiu M, Chen L, Zhong R, Wang J (2021a) Experimental and analytical study of the shear strength and stiffness of studs embedded in high strength concrete. Eng Struct 236:111792
Hu Y, Zhong R, Meloni M, Wang J (2021b) A Novel Shear Strength Prediction Approach for Headed Shear Studs Embedded in Ultrahigh-Performance Concrete. J Struct Eng 147(11):04021181
Hu Z, Shah YI, Yu S (2021c) Cracking analysis of pre-stressed steel–concrete composite girder at negative moment zone. Arab J Sci Eng 46(11):10771–10783
Huang J, Yi W (2021) Time-dependent seismic performance of bridges considering modeling uncertainties under near-field pulse-like ground motions. Journal of Natural Disasters 30(1):99–108
Huang N, Zhou L, Zhou H, Zhou Z (1989) The Research of a System with laser and Microprocessor for Monitoring Tower Displacement of Bridge. Journal of Optoelectronics Laser 8(4):201–203
Huang X, Du W, Wu J (2020) Welding test study for high performance bridge steel Q690qE. Welding Technology 49(5):33–35
Huang I, Chen P, Chen S (2021a) Automated Bridge Coating Defect Recognition Using U-net Fully Convolutional Neural Networks. Journal of the Chinese Institute of Civil and Hydraulic Engineering 33(8):605–617
Huang Z, Chen W, Hao H, Chen Z, Pham TM, Tran TT, Elchalakani M (2021d) Flexural behaviour of ambient cured geopolymer concrete beams reinforced with BFRP bars under static and impact loads. Compos Struct 261:113282
Huang Q, Huang Y, Zheng Q, Song X, Zheng X, Zhang J (2021b) Calculation methods of pylon eccentricity magnified coefficient of Changtai Yangtze River Bridge. J Chang'an Univ (Natural Sci Edition) 41(3):42–51
Huang Y, Chen S, Gu P (2021c) Static and fatigue behavior of shear stud connection embedded in UHPC. Structures 34:2777–2788 (Elsevier)
Huynh T-C (2021) Vision-based autonomous bolt-looseness detection method for splice connections: Design, lab-scale evaluation, and field application. Autom Constr 124:103591
Jafarkarimi M, Khanmohammadi M (2021) Improving Seismic Behavior of Existing Multicolumn RC Bridge Bents Using Low-Damage Retrofit Strategy. J Bridg Eng 26(3):04021006
Janas L (2021) Experimental Study on Vibration and Noise Characteristics of Steel-Concrete Railway Bridge. Sensors 21(23):7964
Jawad FK, Ozturk C, Dansheng W, Mahmood M, Al-Azzawi O, Al-Jemely A (2021) Sizing and layout optimization of truss structures with artificial bee colony algorithm. Structures. 30:546–559 (Elsevier)
Ji W, Liu X (2021) Analysis of the Shear Buckling Strength of Variable-Section Corrugated Steel Webs. KSCE J Civ Eng 25(8):2974–2990
Ji W, Sun B, Bai J, Luo K (2021) Calculation and Analysis of Deflection for Steel-concrete Composite Girder under Long-term Loads. Journal of Hunan University 48(7):51–60
Jia Z, Wen J, Han Q, Du X, Zhang J (2021b) Seismic response of a Reduced-scale continuous girder bridge with rocking Columns: Experiment and analysis. Eng Struct 248:113265
Jia J, Wei B, Bai Y, Wu S, Zhang K, Guo Y (2022) Seismic performance of precast segmental bridge columns reinforced with both stainless-steel bars and GFRP bars. J Bridge Eng 27(1):04021100
Jia D, Mao J, Lv J, Zhang W, Sun J (2021a) Seismic performance of fibre-reinforced polymer and steel double-reinforced bridge piers. Structure and Infrastructure Engineering. pp 1–11
Jiang F, Ding Y, Song Y, Geng F, Wang Z (2021a) Digital Twin-driven framework for fatigue life prediction of steel bridges using a probabilistic multiscale model: Application to segmental orthotropic steel deck specimen. Eng Struct 241:112461
Jiang H, Bai X, Song G, Luo M, Ma X (2021b) Comparing trivariate models for coastal winds and waves accounting for monthly seasonality. Appl Ocean Res 117:102959
Jiang H, Fang H, Liu J, Fang Z, Zhang J (2021c) Experimental investigation on shear performance of transverse angle shear connectors. Structures 33:2050–2060 (Elsevier)
Jiang S, He X, Zou Y, Cai C, L. Zhai L, Nong X (2021d) A wind tunnel test study on the windproof performance of a new type wind-noise barrier for a rail transit vehicle-bridge system. J Vibration Shock, 40(24):230–235 and 298
Jiao C, Liu W, Wu S, Gui X, Huang J, Long P, Li W (2021) Shake table experimental study of curved bridges with consideration of girder-to-girder collision. Eng Struct 237:112216
Jin J, Yang W, Koh H-I, and, (2020) J Park "development of Tuned Particle Impact Damper for Reduction of Transient Railway Vibrations" Applied Acoustics 169:107487
Jin Lim H, Hwang S, Kim H, Sohn H (2021) Steel bridge corrosion inspection with combined vision and thermographic images. Struct Health Monit 20(6):3424–3435
Jing H, Peng T, He X, Zhou J, Zhang S, Zhang H (2021) Experimental study on wind pressure load of closed sound barrier for high-speed railway. Journal of Railway Science and Engineering 18(8):1960–1967
Jutila A, Järvenpää E, Quach TT (2021) Balance and Costs of Cable-Stayed Bridges with Inclined and Curved Tower Shapes. Struct Eng Int 31(4):498–503
Kamar A, Lasheen M, Shaat A, Zaher A, Khalil A (2021) Factors affecting slip and stress distribution of concrete slabs in composite beams. Eng Struct 245:112880
Kasiviswanathan M, Upadhyay A (2021) Web buckling behavior of FRP composite box beams: governing parameters and their effect. Adv Comput Design 6:55–75
Khandel O, Soliman M, Floyd RW, Murray CD (2021) Performance assessment of prestressed concrete bridge girders using fiber optic sensors and artificial neural networks. Struct Infrastruct Eng 17(5):605–619
Kilic G, Caner A (2021) Augmented reality for bridge condition assessment using advanced non-destructive techniques. Struct Infrastruct Eng 17(7):977–989
Kim S-H, Batbold T, Shah SHA, Yoon S, Han O (2021a) Development of shear resistance formula for the Y-type perfobond rib shear connector considering probabilistic characteristics. Appl Sci 11(9):3877
Kim S-H, Han O, Yoon S, Boldoo T (2021b) Shear Resistance Assessment of the Y-Type Perfobond Rib Shear Connector under Repeated Loadings. Appl Sci 11(16):7667

Kong L, Gong J (2021) Experimental study on reinforcement scheme of bridge foundation with anchor bolt static steel pipe pile. Earthquake Resistant Engineering and Retrofitting 43(5):121–128
Kong F, Huang P, Han B, Wang X, Liu C (2021) Experimental study on behavior of corrugated steel-concrete composite bridge decks with MCL shape composite dowels. Eng Struct 227:111399
Korus K, Salamak M, Jasiński M (2021) Optimization of geometric parameters of arch bridges using visual programming FEM components and genetic algorithm. Eng Struct 241:112465
Kruszewski D, Zaghi AE (2021) Load transfer between thin steel plates and ultra-high performance concrete through different types of shear connectors. Eng Struct 227:111450
Kuang Z, Wang H, Zhao Q (2001) Study on Reinforcing Bridge Structures by Gluing Carbon Fibre Reinforced Plastics. Journal of Tongji University (natural Science) 29(8):986–989
Kyprioti AP, Taflanidis AA, Nadal-Caraballo NC, Campbell M (2021) Storm hazard analysis over extended geospatial grids utilizing surrogate models. Coast Eng 168:103855
Lantsoght EOL, Zarate G, Zhang F, Park M-K, Yang Y, Sliedrecht H (2021) Shear experiments of prestressed concrete bridge girders. ACI Struct J 118(3):117–130
Lee J-W, Irish JL, Bensi MT, Marcy DC (2021) Rapid prediction of peak storm surge from tropical cyclone track time series using machine learning. Coast Eng 170:104024
Lei H, Huang J (2021) Seismic Responses Analysis of Train-Track-Bridge System Considering Pile-Soil Interaction. Journal of Southwest Jiaotong University 56(2):229–237
Leng Y, Lu Z-H, Li C-Q, Zhao Y-G (2021) Time-variant probabilistic assessment of corrosion initiation of marine concrete structures considering maximum phenomenon. Constr Build Mater 272:121967
Li X, Fu A (2021) Seismic performance analysis of reinforced concrete beam bridges considering material deterioration. Journal of Lanzhou University of Technology 47(3):139
Li T, Liu Z (2021) An improved continuum model for determining the behavior of suspension bridges during construction. Autom Constr 127:103715
Li H, Zhu Q (2013) Application of paste steel plate method in bridge repair and reinforcement. Technol Innov Application 21:187
Li Z, Ju X, Ju C (2019) Research of high-ductility weather-resistant bridge steel welding materials. Welding Digest of Machinery Manufacturing 3:41–44
Li J, Pan S, Chen Y, Gan M (2021b) The performance of the copulas in estimating the joint probability of extreme waves and surges along east coasts of the mainland China. Ocean Eng 237:109581
Li M, Shao X, Cao J, He G, Chen Y, Wang X (2021c) Performance of experimental and theoretical analysis on shear short headed studs embedded in UHPC. China Journal of Highway and Transport 34(8):191
Li R, Mo T, Yang J, Li D, Jiang S, Wang D (2021d) Bridge inspection named entity recognition via BERT and lexicon augmented machine reading comprehension neural model. Adv Eng Inform 50:101416
Li S, Zhao T, Chu C, Wang J, Alam MS, Tong T (2021e) Lateral cyclic response sensitivity of rectangular bridge piers confined with UHPFRC tube using fractional factorial design. Eng Struct 235:111883
Li Z, Zhu H, Huang M (2021g) A deep learning-based fine crack segmentation network on full-scale steel bridge images with complicated backgrounds. IEEE Access 9:114989–114997
Li X, Gong Z (2021). Analysis of vehicle-induced structure-borne noise characteristics of large-span steel bridge with different structure forms. J Vibration Shock 40(16):91–99 and 158
Li H, Tao D, Huang Y, Bao Y (2012) A data-driven approach for seismic damage detection of shear-type building structures using the fractal dimension of time-frequency features. Structural Control and Health Monitoring
Li H, Wang T, Wu G (2021a) Dynamic response prediction of vehicle-bridge interaction system using feedforward neural network and deep long short-term memory network. Structures 34:2415–2431 (Elsevier)
Li T, Fu W, Li M, Jia G (2021f) Research on design method and application of new isolation system for PVDD device". Low Temp Arch Technol 43(9):59–63+72
Liang F, Liang X, Wang C (2021a) Simplified Added-Mass Model for Evaluating the Response of Rectangular Hollow Bridge Piers under Earthquakes. J Bridg Eng 26(10):04021076
Liang X, Du C, Zhao B, Li Z (2021b) Seismic performance of circular hollow concrete columns. Struct Concrete 22(5):3140–3155
Lin W (2021a) Experimental investigation on composite beams under combined negative bending and torsional moments. Adv Struct Eng 24(7):1456–1465
Lin X (2021b) Comparative experimental study on mechanical properties of hybrid fiber concrete. Chang'an University, Chang'an
Liu Q, Zhang D (2021) Bridge tower design and analysis of chibi yangtze river highway bridge. Journal of Wuhan University of Technology 43(11):63–68
Liu B, Ma J, Liu K, Wang L, Shen R (2021a) Design of a New Type of Composite Saddle for Suspension Bridge. Bridge Construction 51(2):124–130
Liu B, Wang Y, Sun H, Feng M, Chen W (2021b) Study on the energy dissipation of bridge piers using crumb rubber concrete wrapping layer. Earthquake Resistant Engineering and Retrofitting 43(1):140–147
Liu C, Huang Y, Zhang G, Liu W, Liu C, Zhang Y (2021c) Study of Sunlight Temperature Effect of Thin-Walled Hollow High Pier in High Altitude Area. Journal of China & Foreign Highway 41(1):76–79
Liu F, Xu K, Ding W, Qiao Y, Wang L (2021d) Microstructural characteristics and their impact on mechanical properties of steel-PVA fiber reinforced concrete. Cement Concr Compos 123:104196
Liu G, Cui K, Jiang S, Kou Y, You Z, Yu P (2021e) A new empirical distribution for the design wave heights under the impact of typhoons. Appl Ocean Res 111:102679
Liu L, Cui W, Qin J, Liu Q, Song L (2021f) Effects of rail pad viscoelasticity on vibration and structure-borne noise of railway box girder. Journal of Traffic and Transportation Engineering 21(3):134–145
Liu L, Ma ZJ, Zong Z, Tang G (2021g) Blast Response and Damage Mechanism of Prefabricated Segmental RC Bridge Piers. J Bridge Eng 26(4):04021012

Liu T, Feng P, Wu Y, Liao S, Meng X (2021h) Developing an innovative curved-pultruded large-scale GFRP arch beam. Compos Struct 256:113111
Liu Z, Lin Y, Wang Y, Li Y, Shen W (2021j) Based on the CA-CFAR bridge vibration target location and frequency detection method. J Signal Process 37(11):2156–2163
Liu Z-M, Huo X-J, Wang G-M, Ji W-Y (2021k) Test and Numerical Model of Curved Steel-Concrete Composite Box Beams under Positive Moments. Materials 14(11):2978
Liu Y, Xin H, Liu Y (2021i) Experimental and analytical study on tensile performance of perfobond connector in bridge engineering application. Structures 29:714–729 (Elsevier)
Ljubinković F, Martins JP, Gervasio H, da Silva LS, Pedro JO (2019) Experimental behavior of curved bottom flanges in steel box-girder bridge decks. J Constr Steel Res 160:169–188
Lou T, Karavasilis TL, Chen B (2021) Assessment of Second-Order Effect in Externally Prestressed Steel-Concrete Composite Beams. J Bridge Eng 26:04021024
Luo M (2015) Research on data processing and analysis technology of bridge health monitoring system. Chongqing University, Chongqing
Luo B, Ma B (2021) Experimental Study of Fatigue Performance of Steel-UHPC-NC Composite Beam in Negative Moment Zone. Bridge Construction 51(1):58–65
Luo J, Fahnestock LA, LaFave JM (2021a) Seismic Performance Assessment of Quasi-Isolated Highway Bridges with Seat-Type Abutments. J Earthquake Eng 25(11):2285–2324
Luo L, Shan D, Chen F, Chen P (2021b) High-precision calculation method for configuration of completed suspension bridges with pin-connected cable clamps. 工程力学 38(8):133–144
Lydon D, Lydon M, Kromanis R, Dong C-Z, Catbas N, Taylor S (2021) Bridge damage detection approach using a roving camera technique. Sensors 21(4):1246
Ma P, Zhang Y (2022) Modeling asymmetrically dependent multivariate ocean data using truncated copulas. Ocean Eng 244:110226
Ma A, Tan P, Zhou F (2021a) Study on seismic performance of a viscously damped continuous steel truss girder railway bridge with super-high-piers and long-span. Earthquake Engineering and Engineering Dynamics 41(3):95–105
Ma CH, Deng P, Matsumoto T (2021b) Fatigue analysis of a UHPFRC-OSD composite structure considering crack bridging and interfacial bond stiffness degradations. Eng Struct 249:113330
Ma H, Zhou J, He Z, Chen B, Zou Y (2021c) Experimental study on the detection of cracks in typical butt welds of steel bridges based on metal magnetic memory. Highway 66(5):157–162
Ma X, Fan J, Chai X, Li H, Bao X, Li J (2021d) Application of UAV Inspection System in Railway Concrete Bridge Inspection. Railw Eng 61(12):76–80
Ma J (2021) Research on bridge crack recognition and measurement method based on image processing. Master. https://doi.org/10.26944/d.cnki.gbfju.2021.003153
Magalhães F, Cunha Á, Caetano E (2012) Vibration based structural health monitoring of an arch bridge: From automated OMA to damage detection. Mech Syst Signal Process 28:212–228
Maghaghi B, Titoum M, Mazoz A (2021) Experimental evaluation of new channel shear connector shapes. International Journal of Steel Structures 21(3):883–900
Maghsoudi-Barmi A, Khansefid A, Khaloo A, Moeini ME (2021) Probabilistic seismic performance assessment of optimally designed highway bridge isolated by ordinary unbonded elastomeric bearings. Eng Struct 247:113058
Markosian N, Tawadrous R, Mastali M, Thomas RJ, Maguire M (2021) Performance evaluation of a prestressed belitic calcium sulfoaluminate cement (Bcsa) concrete bridge girder. Sustainability 13(14):7875
Mashayekhi M, Santini-Bell E, Eftekhar Azam S (2021) Fatigue crack detection in welded structural components of steel bridges using artificial neural network. J Civ Struct Heal Monit 11(4):931–947
Masri S, Nakamura M, Chassiakos A, Caughey T (1996) Neural network approach to detection of changes in structural parameters. J Eng Mech 122(4):350–360
Mehrsoroush A, Saiidi MS (2021) Analytical Studies of a Novel Bridge Column-Footing Pipe Pin Connection under Lateral Loading. J Bridg Eng 26(2):04020130
Men P, Di J, Jiang H, Zhou X, Qin F (2021a) Web shear buckling of steel–concrete composite girders in negative-moment regions. Eng Struct 237:112210
Men P, Zhou X, Zhang Z, Di J, Qin F (2021b) Behaviour of steel–concrete composite girders under combined negative moment and shear. J Constr Steel Res 179:106508
Meng F, Song T, Xu D, Xie P, Li Y (2021) Forecasting tropical cyclones wave height using bidirectional gated recurrent unit. Ocean Eng 234:108795
Miao R, Shen R, Tang F, Chen W, Que M (2021a) Nonlinear interaction effect on main cable clamp bolts tightening in suspension bridge. J Constr Steel Res 182:106663
Miao R, Shen R, Wang L, Bai L (2021b) Theoretical and numerical studies of the slip resistance of main cable clamp composed of an upper and a lower part. Adv Struct Eng 24(4):691–705
Ministry of communications (2021) Statistical bulletin of transportation industry development in 2020. Finance & Accounting for Communications (6):92–97.
Mohammad S, Petros S, and L. A B. (2021) Experimental testing of hybrid sliding-rocking bridge columns under torsional and biaxial lateral loading. Earthquake Eng Struct Dynamics 50 (10):2817–2837
Na WS (2021) Bolt loosening detection using impedance based non-destructive method and probabilistic neural network technique with minimal training data. Eng Struct 226:111228
Nasiri A, Shimozato T, Mumtaz Y (2021) Experimental study on the post-cracking behavior of preflex beams under cyclic loading. Structures 26:1390–1403 (Elsevier)
Nguyen ST, La HM (2021) A climbing robot for steel bridge inspection. J Intell Rob Syst 102(4):1–21
Nguyen TQ (2021) A deep learning platform for evaluating energy loss parameter in engineering structures. Structures. pp 1326–1345
Ni YQ, Chen R (2021) Strain monitoring based bridge reliability assessment using parametric Bayesian mixture model. Eng Struct 226:111406

Ni Y, Zhang Q, Xin R (2021) Magnetic flux detection and identification of bridge cable metal area loss damage. Measurement 167:108443
Nicoletti RS, Rossi A, de Souza ASC, Martins CH (2021) Numerical assessment of effective width in steel-concrete composite box girder bridges with partial interaction. Eng Struct 239:112333
Nili MH, Taghaddos H, Zahraie B (2021) Integrating discrete event simulation and genetic algorithm optimization for bridge maintenance planning. Autom Constr 122:103513
Nour NA, Vié D, Chateauneuf A, Amziane S, Kallassy A (2021) Dimensioning of partially prestressed concrete beams, optimization of T-shaped section with heels. Eng Struct 235:112054
Oppong K, Saini D, Shafei B (2021) Ultrahigh-Performance Concrete for Improving Impact Resistance of Bridge Superstructures to Overheight Collision. J Bridg Eng 26(9):04021060
Ou K, Luo K, Lei X (2021) Application of damping plate in noise control of elevated track box girder structure. J Vibration Shock 40(5):230–236
Pan X, Yang TY (2022) Image-based monitoring of bolt loosening through deep-learning-based integrated detection and tracking. Computer-Aided Civil and Infrastructure Engineering 37(10):1207–1222
Pang Y, He W, Zhong J (2021a) Risk-based design and optimization of shape memory alloy restrained sliding bearings for highway bridges under near-fault ground motions. Eng Struct 241:112421
Pang Y, Zhou X, He W, Zhong J, Hui O (2021b) Uniform design–based Gaussian process regression for data-driven rapid fragility assessment of bridges. J Struct Eng 147(4):04021008
Peng X, Zhong X, Zhao C, Chen A, Zhang T (2021) A UAV-based machine vision method for bridge crack recognition and width quantification through hybrid feature learning. Constr Build Mater 299:123896
Pimentel R, Ribeiro D, Matos L, Mosleh A, Calçada R (2021) Bridge Weigh-in-Motion system for the identification of train loads using fiber-optic technology. Structures. pp 1056–1070
Pineda Allen JC, Ng CT (2021) Nonlinear guided-wave mixing for condition monitoring of bolted joints. Sensors 21(15):5093
Pirdayr A, Mohammadi M, Kazemzadeh-Parsi MJ, Rajabi M (2021) Self-loosening effects on vibration characteristics of plates with bolted joints: An experimental and finite element analysis. Measurement 185:109922
Pnevmatikos NG, Hatzigeorgiou GD (2017) Damage detection of framed structures subjected to earthquake excitation using discrete wavelet analysis. Bull Earthq Eng 15(1):227–248
Qi, D., X. Chen, Y. Zhu, and Q. Zhang. (2021) A new type of wind-resistance cable net for narrow suspension bridges and wind-resistance cable element for its calculation. Elsevier, pp 4243–4255.
Qiao C, Myers AT (2022) Surrogate modeling of time-dependent metocean conditions during hurricanes. Nat Hazards 110(3):1545–1563
Qin Q (2000) Health monitoring of long-span bridges. China Journal of Highway and Transport 13(2):39–44
Qin X, Ni A, Han Y, Cao L, Huang Z (2020) Noise reduction performance of highway sonic crystals noise barrier. China Environ Sci 40(12):5493–5501
Qin A, Liu S, Ji W, Li A, Chen Z (2021a) Analysis on torsion performance of single-box twin-cell composite box girder with corrugated steel webs and steel bottom plates. Journal of Southeast University (natural Science Edition) 51(5):740–746
Qin X, Li Q, Ding X, Xie L, Wang C, Liao M, Zhang L, Zhang B, Xiong S (2021b) A structure knowledge-synthetic aperture radar interferometry integration method for high-precision deformation monitoring and risk identification of sea-crossing bridges. Int J Appl Earth Obs Geoinf 103:102476
Qu K, Sun WY, Kraatz S, Deng B, Jiang CB (2020a) Effects of floating breakwater on hydrodynamic load of low-lying bridge deck under impact of cnoidal wave. Ocean Eng 203:107217
Qu K, Wen BH, Ren XY, Kraatz S, Sun WY, Deng B, Jiang CB (2020b) Numerical investigation on hydrodynamic load of coastal bridge deck under joint action of solitary wave and wind. Ocean Eng 217:108037
Qu H, Fu J, Li T, Wu C, Sun X, Wei H, Wang Z (2021) Experimental and numerical assessment of precast bridge columns with different grouted splice sleeve coupler designs based on shake table test. J Bridg Eng 26(8):04021055
Quan X, Lv H, Liu C, Wang H, Wu D, Chen P, Zhou H (2021) An investigation on bolt stress ultrasonic measurement based on acoustic time difference algorithm with adaptive hybrid extended Kalman filter. Measurement 186:110223
Rachedi M, Matallah M, Kotronis P (2021) Seismic behavior & risk assessment of an existing bridge considering soil-structure interaction using artificial neural networks. Eng Struct 232:111800
Rajabi M, Ghassemi H, Ghafari H (2021) Homogeneous Wave Load Effects on the Connections of Main Parts of Side-Anchored Straight Floating Bridge. Mathematical Problems Eng 1:1–15
Ran J, Li T, Chen D, Shang L, Li W, Zhu Q (2021) Mechanical properties of concrete reinforced with corrugated steel fiber under uniaxial compression and tension. Structures. pp 1890–1902
Reggiani Manzo N, Vassiliou MF, Mouzakis H, Badogiannis E (2022) Shaking table tests of a resilient bridge system with precast reinforced concrete columns equipped with springs. Earthquake Eng Struct Dynam 51(1):213–239
Sadeghi F, Zhu X, Li J, Rashidi M (2021) A novel slip sensory system for interfacial condition monitoring of steel-concrete composite bridges. Remote Sensing 13(17):3377
Safari M, Ghasemi SH, Taghia SAHS (2021) Target reliability analysis of bridge piers concerning the earthquake extreme event limit state. Eng Struct 245:112910
Salawu O (1997) Detection of structural damage through changes in frequency: a review. Eng Struct 19(9):718–723
Samadi D, Taghaddos H, Nili MH, Noghabaei M (2021) Development of a Bridge Maintenance System Using Bridge Information Modeling. Civil Engineering Infrastructures Journal 54(2):351–364
Sarwar MZ, Cantero D (2021) Deep autoencoder architecture for bridge damage assessment using responses from several vehicles. Eng Struct 246:113064
Sastry KGK, Sahitya P, Ravitheja A (2021) Influence of nano TiO2 on strength and durability properties of geopolymer concrete. Materials Today: Proceedings 45:1017–1025
Saxena R, Gupta T, Sharma RK, Panwar NL (2021) Influence of granite waste on mechanical and durability properties of fly ash-based geopolymer concrete. Environ Dev Sustain 23(12):17810–17834

Serwa A, Saleh M (2021) New semi-automatic 3D registration method for terrestrial laser scanning data of bridge structures based on artificial neural networks. The Egyptian Journal of Remote Sensing and Space Science 24(3):787–798
Shamsi M, Zakerinejad M, Vakili AH (2021) Seismic analysis of soil-pile-bridge-train interaction for isolated monorail and railway bridges under coupled lateral-vertical ground motions. Eng Struct 248:113258
Shao H, Liang L, Gao S (2021a) Damage identification based on convolutional self coding neural network. Scientific and Technological Innovation 11:140–141
Shao X, He G, Shen X, Zhu P, Chen Y (2021b) Conceptual design of 1000 m scale steel-UHPFRC composite truss arch bridge. Eng Struct 226:111430
Shen Z, Wei K (2021) Stochastic model of tropical cyclones along China coast including the effects of spatial heterogeneity and ocean feedback. Reliab Eng Syst Saf 216:108000
Sheng X, Cheng G, D. THOMPSON, and S. Ge. (2021) Research progress on wheel-rail noise prediction models. Journal of Traffic and Transportation Engineering 21(3):20–38
Shi G, Li G (2021) Evaluation of fatigue life of stud in steel-UHPC composite structure based on fracture mechanics. Journal of chang'an University (natural Science Edition) 41(2):102–113
Shi W, Shafei B, Phares B (2021a) Structural capacity and fatigue performance of ASTM A709 Grade 50CR steel. Constr Build Mater 270:121379
Shi Z, Jiang X, Gao G, Ning B, Yu M (2021c) Mechanical Property Analysis of Steel-Concrete Joint Section of Long-Span High-Speed Railway Hybrid Girder Cable-Stayed Bridge. Bridge Construction 51(2):62–70
Shi X, Liang Y, Wan D, Chen H, Fang L (2021b) Buckling Analysis of Guide Beams in Bridge Jacking Construction and Study on Reinforcement Measures. J Zhengzhou Univ (Eng Sci) 42(5):74–78
Shirahata H, Hirayama S, Ono S, Yamase Y (2021) Detection of crack in painted flange gusset welded joint by ultrasonic test. Welding in the World 65(11):2147–2156
Shoushtari E, Saiidi MS, Itani A, Moustafa MA (2021) Analytical studies and design of steel plate girder ABC bridges under seismic loads. Eng Struct 227:111453
Shrestha S, Kannan M, Morscher GN, Presby MJ, Razavi SM (2021) In-situ fatigue life analysis by modal acoustic emission, direct current potential drop and digital image correlation for steel. Int J Fatigue 142:105924
Sjaarda M, West JS, Walbridge S (2021) Reliability analysis of welded stud shear connectors on simply-supported bridge girders. Can J Civ Eng 48(6):604–615
Soleimani F, Liu X (2022) Artificial neural network application in predicting probabilistic seismic demands of bridge components. Earthquake Eng Struct Dynam 51(3):612–629
Son H, Jang Y, Kim S-E, Kim D, Park J-W (2021a) Deep Learning-Based Anomaly Detection to Classify Inaccurate Data and Damaged Condition of a Cable-Stayed Bridge. IEEE Access 9:124549–124559
Son H, Pham V-T, Jang Y, Kim S-E (2021b) Damage localization and severity assessment of a cable-stayed bridge using a message passing neural network. Sensors 21(9):3118
Song C, Zhang G, Kodur V, Zhang Y, He S (2021a) Fire response of horizontally curved continuous composite bridge girders. J Constr Steel Res 182:106671
Song J, Bi K, Xu K, Han Q, Du X (2021b) Seismic responses of adjacent bridge structures coupled by tuned inerter damper. Eng Struct 243:112654
Song T, Walter Yang CS, Scott DW, Shen Y, Li G (2021c) Novel finite element analysis of curved concrete box girders using hybrid box elements. J Struct Eng 147(1):04020284
Spanos P, Giaralis A, Politis N (2007) Time–frequency representation of earthquake accelerograms and inelastic structural response records using the adaptive chirplet decomposition and empirical mode decomposition. Soil Dyn Earthq Eng 27(7):675–689
State Administration for Market Regulation (2020) Steel for large wire energy welding :GB/T38817–2020.
Su H, Su Q, Xu C, Zhang X, Lei D (2021a) Shear performance and dimension rationalization study on the rubber sleeved stud connector in continuous composite girder. Eng Struct 240:112371
Su Q, Su H, Wu F (2021b) Mechanical analysis of the influence of rubber sleeved stud connector on the steel-concrete composite girder. Journal of Tongji University (natural Science) 49(8):1079–1087
Su S, Yang Y, Wang W, Ma X (2021c) Crack propagation characterization and statistical evaluation of fatigue life for locally corroded bridge steel based on metal magnetic memory method. J Magn Magn Mater 536:168136
Sun M, Pang Y, Du C, Li X, Wu Y (2021a) Optimization of Mo on the corrosion resistance of Cr-advanced weathering steel designed for tropical marine atmosphere. Constr Build Mater 302:124346
Sun B, Yang Y, Li X, Yan M, Xie M, Bao Y (2022) Full-scale investigation of post-tensioned prestressed concrete bridge girders subjected to frost heaving in cold regions. Eng Struct 250:113413
Sun W, Fan X, Wang X, Li L, Wu Z (2021b) Seismic performance of medium-span continuous beam bridges in high intensity mountainous areas based on different seismic structural systems. J Chang'an Univ (Natural Sci Edition) 41(2):125–134
Suzuki A, Kimura Y (2021) Mechanical performance of stud connection in steel-concrete composite beam under reversed stress. Eng Struct 249:113338
Suzuki A, Suzuki K, Kimura Y (2021) Ultimate shear strength of perfobond shear connectors subjected to fully reversed cyclic loading. Eng Struct 248:113240
Tabet-Derraz, M. I., A. Khelil, K. Hamdaoui, N. Boumechra, and M. Abdallah. (2021) "Experimental and numerical study of an innovative OMEGA-shaped connector for composite beams." Structures, 279–297. Elsevier.
Tang Y, Yue J, Hua X (2021a) Local stiffness correction for finite element model of bridge by employing artificial bee colony algorithm. Journal of Railway Science and Engineering 18(9):2333–2343
Tang Z-F, Sui X-D, Duan Y-F, Zhang P, Yun CB (2021b) Guided wave-based cable damage detection using wave energy transmission and reflection. Struct Control Health Monit 28(5):e2688
Tian K, Ožbolt J (2021) Concrete pry-out failure of single headed stud anchors after fire exposure: Experimental and numerical study. Eng Struct 232:111816

Tochaei EN, Fang Z, Taylor T, Babanajad S, Ansari F (2021) Structural monitoring and remaining fatigue life estimation of typical welded crack details in the Manhattan Bridge. Eng Struct 231:111760
Todorov, B., and A. M. Billah. (2021) Seismic fragility and damage assessment of reinforced concrete bridge pier under long-duration, near-fault, and far-field ground motions. Structures, 671–685. Elsevier.
Todorovska MI, Trifunac MD (2010) Earthquake damage detection in the Imperial County Services Building II: analysis of novelties via wavelets. Struct Control Health Monit 17(8):895–917
Tu B, Cai S, Li J, Liu H (2021a) Fatigue assessment of a full-scale composite box-girder with corrugated-steel-webs and concrete-filled-tubular flange. J Constr Steel Res 183:106768
Tu W, Gu X, Chen H-P, Fang T, Geng D (2021b) Time domain nonlinear kinematic seismic response of composite caisson-piles foundation for bridge in deep water. Ocean Eng 235:109398
Tzouka, E., T. Karavasilis, M. M. Kashani, and S. Afshan. (2021) Finite element modelling of push-out tests for novel locking nut shear connectors. Structures, 1020–1032. Elsevier.
Van Staen G, Fang H, Van Bogaert P, De Backer H (2021) Ultimate Shear Load Capacity of Cross-sectional Curved Steel Webs. Struct Eng Int 31(2):188–199
Vigneri V, Odenbreit C, Romero A (2021) Numerical study on design rules for minimum degree of shear connection in propped steel–concrete composite beams. Eng Struct 241:112466
Wan X, Wu K, Wang H, Li G (2015) Applications of oxide metallurgy technology on high heat input welding steel. China Metallurgy 6:6–12
Wan H-P, Su L, Frangopol DM, Chang Z, Ren W-X, Ling X (2021) Seismic Response of a Bridge Crossing a Canyon to Near-Fault Acceleration-Pulse Ground Motions. J Bridg Eng 26(6):05021006
Wang L (2021a) Study on Chemical Admixture for Long-life Concrete in Extreme Environment. China Concrete 9:34–38
Wang J, Liu PL-F (2021) Numerical study on impacts of a concurrent storm-tide-tsunami event in Macau and Hong Kong. Coast Eng 170:104000
Wang Z, Qiu W (2021) Characteristics of wave forces on pile group foundations for sea-crossing bridges. Ocean Eng 235:109299
Wang J, Feng L, Zou B (2006) Review on Concrete Bridge Strengthening and a Typical Example. Hunan Communication Science and Technology 32(3):130–133
Wang X, Zhang C, Wang W, Zhou C (2011) Study and application of large-scale concrete beams strengthened with CFRP laminate. Composites Science and Engineering 5:77–79
Wang B, Zhu F, Wang C (2019) Application of oxide metallurgy in high heat input welding steels. Iron & Steel 54(9):12–21
Wang D, Tan B, Wang L, Chen F, Xiang S (2021a) Numerical Study on Stress Intensity Factors for Stud Connectors of Steel-Concrete Connection. International Journal of Steel Structures 21(5):1775–1789
Wang D, Tan B, Wang X, Zhang Z (2021b) Experimental study and numerical simulation of temperature gradient effect for steel-concrete composite bridge deck. Measurement and Control 54(5–6):681–691
Wang D, Xia Q, Sun Z, Wang D, Liu D (2021c) Seismic Fragility Comparative Research of Sea-crossing Bridges with Scour Conditions Under Onshore and Offshore Ground Motions. Advanced Engineering Sciences 53(5):127–137
Wang F, Gu M, Chen Q, Zhao Z, Luo J (2021d) Experimental study on stability of orthotropic steel box girder of self-anchored suspension cable-stayed bridge. Thin-Walled Structures 163:107727
Wang F, Tian L, Zhao Z, Chen Q, Mei H (2021e) Stability of full-scale orthotropic steel plates under axial and biased loading: Experimental and numerical studies. J Constr Steel Res 181:106613
Wang H, Sun T, Liu X, Tang C, Wang J, Chen A (2021f) Experimental Investigation on Flexural Capacity of Steel-UHPC Continuous Composite Girder. China Journal of Highway and Transport 34(8):218
Wang H, Sun T, Shao X, Tang C, Yang L (2021g) Static behavior of a steel-ultra high performance concrete continuous composite box girder. Struct Infrastruct Eng 18(8):1120–1137
Wang J, Sheng J, Jiang J, Wen J, Xiao S, Zhang Z (2021h) Identification method of bolt looseness using STFT-IP time-frequency feature extraction technology. Noise and Vibration Control 41(3):108–112
Wang L, Liu S, Lu W, Niu S, Shi X (2021i) Temperature effect of new-type composite box girder with corrugated steel webs. Journal of ZheJiang University (engineering Science) 55(4):675–683
Wang L, Shen R, Zhang S, Bai L, Zhen X, Wang R (2021j) Strand element analysis method for interaction between cable and saddle in suspension bridges. Eng Struct 242:112283
Wang P, Chang K, Dzeng D, Lin T, Hung H, Cheng W (2021k) Seismic evaluation of reinforced concrete bridges using capacity-based inelastic displacement spectra. Earthquake Eng Struct Dynam 50(7):1845–1863
Wang P, Long P, Zhao M, Zhang C, Du X (2021l) Analytical solution of earthquake-induced hydrodynamic pressure on arrays of circular cylinders considering high-order scattered waves. J Eng Mech 147(9):04021051
Wang R, Ma B, Chen X (2021m) Seismic performance of pre-fabricated segmental bridge piers with grouted splice sleeve connections. Eng Struct 229:111668
Wang S, Fang Z, Chen G, Jiang H, Teng S (2021n) Numerical analysis on shear behavior of grouped head stud shear connectors between steel girders and precast concrete slabs with high-strength concrete-filled shear pockets. J Bridg Eng 26(6):04021030
Wang S, Xu W, Wang J, Xin G, Chen Y, Zhao Z, Bai Y (2021o) Experimental research on anti-seismic reinforcement of fabricated concrete pier connected by grouting sleeve based on CFRP and PET materials. Eng Struct 245:112838
Wang S, Zhang Y, Luo T, Liu Y (2021p) Elastic critical shear buckling stress of large-scale corrugated steel web used in bridge girders. Eng Struct 244:112757
Wang W, Shen A, Lyu Z, He Z, Nguyen KT (2021q) Fresh and rheological characteristics of fiber reinforced concrete——A review. Constr Build Mater 296:123734
Wang W, Zhang X, Ding F, Zhou X (2021s) Finite element analysis on shear behavior of high-strength bolted connectors under inverse push-off loading. Energies 14(2):479
Wang X, He Q, An Z, Liu G, Wen X, Wang Y, Zhong Z (2021t) Experimental Study of Perfobond Rib Shear Connector under Lateral Force. Appl Sci 11(19):9088
Wang X, Wang H, Zhang J, Sun Y, Bai Y, Zhang Y, Wang H (2021v) Form-finding method for the target configuration under dead load of a new type of spatial self-anchored hybrid cable-stayed suspension bridges. Eng Struct 227:111407

Wang X, Wu S, Jia J, Li H, Wei Y, Zhang K, Bai Y (2021w) Experimental evaluation of seismic performance of corroded precast RC bridge columns and the retrofit measure using CFRP jackets. Eng Struct 245:112872
Wang Y, Shao X, Zhang X, Cao J, Zhao X, Deng S (2021x) Structural Behaviors of a Low-Profile Steel Plate-Reinforced UHPC Deck Panel with Longitudinal Ribs. J Bridg Eng 26(8):04021043
Wang Y, Wang P, Tang H, Liu X, Xu J, Xiao J, Wu J (2021y) Assessment and prediction of high speed railway bridge long-term deformation based on track geometry inspection big data. Mech Syst Signal Process 158:107749
Wang Z, Zhang W, Fang R, Zhao H (2021z) Dynamic Model Testing of Low-Gravity-Center Cable-Stayed Bridges with Different Girder-to-Tower Connections. J Bridg Eng 26(1):04020112
Wang, W., Z. Yi, B. Tian, Y. Zhang, and S. Lu. (2021r) Nonlinear finite element analysis of PBL shear connectors in hybrid structures. Structures, 4642–4654. Elsevier.
Wang, X., C. Miao, and X. Wang. (2021u) Prediction analysis of deflection in the construction of composite box-girder bridge with corrugated steel webs based on MEC-BP neural networks. Structures, 691–700. Elsevier.
Wang Z, Zhou X, Liu Z (2021aa) Panting Fatigue of Trapezoidal Corrugated Steel Webs with Mixed-Mode Cracks. Int J Steel Struct 21(2):576–589
Wang P (2021b) Ultrasonic guided wave detection methods for fatigue cracks in orthotropic steel bridge decks. Harbin Institute of Technology, Harbin
Wei Z (2021) Forecasting wind waves in the US Atlantic Coast using an artificial neural network model: Towards an AI-based storm forecast system. Ocean Eng 237:109646
Wei B, Hu Z, He X, Jiang L (2021a) System-based probabilistic evaluation of longitudinal seismic control for a cable-stayed bridge with three super-tall towers. Eng Struct 229:111586
Wei B, Hu Z, Zuo C, Wang W, Jiang L (2021b) Effects of horizontal ground motion incident angle on the seismic risk assessment of a high-speed railway continuous bridge. Archives of Civil and Mechanical Engineering 21(1):1–20
Wei J, Li J, Wu C, Liu Z, Li J (2021c) Hybrid fibre reinforced ultra-high performance concrete beams under static and impact loads. Eng Struct 245:112921
Wei M-W, Xie J-H, Li J-L, Xiang C-Y, Huang P-Y, Liu F (2021d) Effect of the chloride environmental exposure on the flexural performance of strengthened RC beams with self-anchored prestressed CFRP plates. Eng Struct 231:111718
Wei W, Yuan Y, Igarashi A, Zhu H, Tan P (2021e) Experimental investigation and seismic fragility analysis of isolated highway bridges considering the coupled effects of pier height and elastomeric bearings. Eng Struct 233:111926
Wen J, Han Q, Xie Y, Du X, Zhang J (2021) Performance-based seismic design and optimization of damper devices for cable-stayed bridge. Eng Struct 237:112043
Wen BH, Qu K, Lan GY, Sun WY, Yao Y, Deng B, Jiang CB (2022) Numerical study on hydrodynamic characteristics of coastal bridge deck under joint action of regular waves and wind. Ocean Eng 245:110450
Wen X, Limin S (2021) Assessment and mitigation on near-fault earthquake wave effects on seismic responses and pile-soil interactions of soil-pile-bridge model. Soil Dynamics and Earthquake Engineering. p 143
"Wikipedia: 1915 Çanakkale Bridge." 2022. https://en.wikipedia.org/wiki/1915_%C3%87anakkale_Bridge.
"Wikipedia: El Ferdan Railway Bridge." 2022. https://en.wikipedia.org/wiki/El_Ferdan_Railway_Bridge.
Wu Q (2005) Concrete bridge strengthening technology. Highway 4:83–85
Wu F, Liu S, Xue C, Yang K, Feng Y, Zhang H (2021a) Experimental study on the mechanical properties of perfobond rib shear connectors with steel fiber high strength concrete. Materials 14(12):3345
Wu Q, Jiang R, Xu T, Chen Y, Nie X (2021b) Analysis on shear-lag effect of composite box girders with corrugated steel webs considering shear deformation of webs. Journal of Building Structures 42:220–228
Wu X, Zhao J, Liu C (2021d) Bridge crack detection algorithm based on CNN and CRF. Computer Eng Design 42(1):51–56
Wu Z, Chen J, Jiang C, Deng B (2021e) Simulation of extreme waves using coupled atmosphere-wave modeling system over the South China Sea. Ocean Eng 221:108531
Wu Q, Xiao Y, Guo Z, Dong J, Xu T, Yue Y, Fang Y (2021c) Shear force distribution on the web of single box multi-cell composite girders with corrugated steel webs. Prog Steel Building Struct 23(8):61–6675
Xia Z, Lin Y, Wang Q, Fan Q (2021) Damage detection method for cables based on the change rate of wavelet packet total energy and a neural network. J Civ Struct Heal Monit 11(3):593–608
Xiao H, Luo L, Shi J, Jiang H, Wu Z (2021a) Stressing state analysis of multi-span continuous steel-concrete composite box girder. Eng Struct 246:113070
Xiao J-L, Zhou M, Nie J-G, Yang T-Y, Fan J-S (2021b) Flexural behavior of steel-UHPC composite slabs with perfobond rib shear connectors. Eng Struct 245:112912
Xie X, Huang Y, Qin X (2021) A New Composite Truss Bridge and a Study on Its Dynamic Characteristics with FE and Experimental Methods. KSCE J Civ Eng 25(3):931–947
Xiong X-H, Yang B, Wang K-W, Liu T, He Z, Zhu L (2020) Full-scale experiment of transient aerodynamic pressures acting on a bridge noise barrier induced by the passage of high-speed trains operating at 380–420 km/h. J Wind Eng Ind Aerodyn 204:104298
Xu G, Wang Y, Wang S, Wang L (2017) Key Construction Techniques for Strengthening of Main Girder of Dongming Huanghe River Highway Bridge. Bridge Construction 47(5):101–106
Xu C, Xiao H, Zhang B, Fu J, Masuya H (2021a) Fatigue behavior of steel fiber reinforced concrete composite girder under high cycle negative bending action. Eng Struct 241:112432
Xu F, Yang J, Zhang Z, Zhang M (2021b) Investigations on large-amplitude vibrations of rigid models using a novel testing device. J Bridg Eng 26(5):06021002
Xu J, Sun H, Chen W, Guo X (2021c) Experiment-Based Fatigue Behaviors and Damage Detection Study of Headed Shear Studs in Steel-Concrete Composite Beams. Appl Sci 11(18):8297
Xu J-G, Cai Z-K, Feng D-C (2021d) Life-cycle seismic performance assessment of aging RC bridges considering multi-failure modes of bridge columns. Eng Struct 244:112818
Xu W, Ma B, Duan X, Li J (2021f) Experimental investigation of seismic behavior of UHPC connection between precast columns and footings in bridges. Eng Struct 239:112344
Xu X, He D, Zeng S, He W, Tan H, Yu Z (2021g) Effect of concrete cracks on the corrosion of headed studs in steel and concrete composite structures. Constr Build Mater 293:123440

Xu X, Zhang T, Wu W, Jiang S, Yang J, Liu Z (2021h) Optimizing the resistance of Ni-advanced weathering steel to marine atmospheric corrosion with the addition of Al or Mo. Constr Build Mater 279:122341
Xu X, Zhou X, Liu Y (2021i) Fatigue life prediction of rubber-sleeved stud shear connectors under shear load based on finite element simulation. Eng Struct 227:111449
Xu Y, Bao Y, Chen J, Zuo W, Li H (2019) Surface fatigue crack identification in steel box girder of bridges by a deep fusion convolutional neural network based on consumer-grade camera images. Struct Health Monitoring 18(3):653–674 (SAGE Publications Sage UK: London, England.)
Xu, Q., K. Lu, J. Wang, and Y. Yao. (2021e) Performance of large-diameter studs in thin ultra-high performance concrete slab. Structures, 4936–4951. Elsevier.
Yan Y, Mao Z, Wu J, Padir T, Hajjar JF (2021b) Towards automated detection and quantification of concrete cracks using integrated images and lidar data from unmanned aerial vehicles. Struct Control Health Monit 28(8):e2757
Yan C, Zhao J, Liu S, Zhang J (2021a) Seismic Flexural Strength of Reinforced Concrete Columns Corroded by Saline Soil. ACI Structural J 118(2):6763–6788
Yang R (2021a) Surface disease detection system of steel structure bridge based on image processing. Huazhong Normal University, Wuhan
Yang Y, Nagarajaiah S (2014) Blind identification of damage in time-varying systems using independent component analysis with wavelet transform. Mech Syst Signal Process 47(1–2):3–20
Yang J, Chen B, Wu X, Su J, Huang Q (2021a) Influence of the fresh ultra-high performance fiber reinforced concrete flowability on its compressive strength. Acta Materiae Compositae Sinica 38(11):3827–3837
Yang J, Zeng J, He X, Hu H, Su Y, Bai H, Tan H (2021b) Eco-friendly UHPC prepared from high volume wet-grinded ultrafine GGBS slurry. Constr Build Mater 308:125057
Yang S, Mavroeidis GP, Tsopelas P (2021c) Seismic response study of ordinary and isolated bridges crossing strike-slip fault rupture zones. Earthquake Eng Struct Dynam 50(11):2841–2862
Yang Y, Chen J, Zhang S (2021d) Seismic performance evaluation of existing highway bridges based on fuzzy analytic hierarchy process. Building Structure 51(S2):581–585
Yang Z, Huang B, Zhu B, Zhang J, Kang A (2021e) Comparative study of tsunami-like wave-induced forces on medium-scale models of box girder and T-girder bridges. J Bridg Eng 26(2):04020125
Yang Z, Yang M, Rong X, Tian L (2021f) Theoretical and numerical study on dynamic characteristics of composite trough girder with corrugated steel webs. J Bridg Eng 26(3):04021008
Yang S, Ding S (2021) A Method for Bridge Damage Identification and Evaluation Based on Strain Ratio. J Highway Trans Res Dev 38(1):87–96+111
Yang, W. (2021b) Fiber-Reinforced Magnesium Phosphate Cement-Based Nanocomposites in the Field of Bridge Structure Repair and Strengthening. Adv Mater Sci Eng, 2021b.
Yao W, Draper S, An H, Cheng L, Harris JM, Whitehouse RJ (2021a) Experimental study of local scour around submerged compound piles in steady current. Coast Eng 165:103831
Yao Y, Yan M, Shi Z, Wang Y, Bao Y (2021b) Mechanical behavior of an innovative steel–concrete joint for long-span railway hybrid box girder cable-stayed bridges. Eng Struct 239:112358
Ye M, Guo Z, Chen C, Chen Y (2021) Shaking table test study on seismic performance of UHPC rectangular hollow bridge pier. Compos Struct 275:114435
Yi L, Yuan Y, Peng Z (2021) Engineering Application of 690 MPa High-Performance Bridge Steel. Bridge Construction 51(5):14–19
Ying L, Yang S, Xu H (2022) Design and practice of main structure of pi river main canal aqueduct. China Municipal Eng 1:1–3+118
Yoshiaki M, Atsuhiro O, Tokihide O, Yui I, Takahide S (2018) Development of automatic crack detection device for bead-penetrating crack in orthotropic steel deck by temperature gap method using infrared thermography. J Struct Eng 64:573–582 (公益社団法人 土木学会)
Yoshitake H, Hasegawa H (2021) Moving-wheel fatigue durability of cantilever bridge deck slab strengthened with high-modulus CFRP rods. Structures. pp 2406–2414
Yu E, Wei H, Han Y, Hu P, Xu G (2021a) Application of time series prediction techniques for coastal bridge engineering. Advances in Bridge Engineering 2(1):1–18
Yu J, Jiang L, Zhou W, Lu J, Zhong T, Peng K (2021b) Study on the influence of trains on the seismic response of high-speed railway structure under lateral uncertain earthquakes. Bull Earthq Eng 19(7):2971–2992
Yu S, Xu Z, Su Z, Zhang J (2021c) Two flexible vision-based methods for remote deflection monitoring of a long-span bridge. Measurement 181:109658
Yu Y, Liu Y, Chen J, Jiang D, Zhuang Z, Wu X (2021d) Detection method for bolted connection looseness at small angles of timber structures based on deep learning. Sensors 21(9):3106
Yuan M (2021) The Influence of Climatic Conditions on Concrete Strength and Impermeability in Plateau Areas. Construction & Design for Engineering 15:134–136
Yuan C, Chen W, Hao H, Kong Q (2021a) Near real-time bolt-loosening detection using mask and region-based convolutional neural network. Struct Control Health Monit 28(7):e2741
Yuan P, Zhu D, Dong Y (2021b) Spatial failure mechanism of coastal bridges under extreme waves using high-efficient pseudo-fluid-structure interaction solution scheme. Ocean Eng 240:109894
Yuan R, Fu Z, Zheng Q, Xu L, Ma R (2021c) Methods to Compute Eccenticity Modifying Factor of High-Rise Bridge Tower. Bridge Construction 51(5):37–43
Yuan S, Duan W, Zhou C, Chen N (2021d) Analysis of shear lag effect of extradosed cable-stayed bridges with corrugated steel webs during construction. Journal of Central South University (science and Technology) 52(11):4055–4062
Zeng Z (2019b) Key Techniques for Bridge Pier Reconstruction of a Railway Bridge on Huanghe River. Bridge Construction 49(4):113–118
Zeng Z (2019a) Analysis of the overall stress of arch rib during hoisting of long span steel tube arch bridge by cable-stayed hook. Sichuan Arch 39(3):168–170+174

Zhan Y, Lu S, Zheng Y, Jiang H, Xiong S (2021b) Theoretical Study on the Influence of Welding Collar on the Shear Behavior of Stud Shear Connectors. KSCE J Civ Eng 25(4):1353–1368
Zhan, Y., M. Duan, L. Zhang, C. Liu, Z. Li, and R. Zhao. (2021a) Study on the shear performance of adhesive shear connectors in push-out tests. Structures, 2103–2117. Elsevier.
Zhang D, Zhou J, Wang D (2019) Design of main girder of chibi changjiang river highway bridge. Bridge Construction 49(4):81–85
Zhang M, Qian Y, Zhang F, Zhu S (2020a) Experimental analysis of spatial force performance of concrete-reinforced stone arch bridge based on enlarged section method. Journal of Jilin University: Engineering and Technology Edition 50(1):210–215
Zhang Y, Zheng K, Heng J, Feng X, Wang Y (2020b) State-of-the-art review of the fatigue performance of corroded weathering steel and high performance steel in 2019. Journal of Civil and Environmental Engineering 42(5):89–97
Zhang B-Z, Song Y-J, Wang K-H, Lu G-Y, Li N (2021a) Study of Influence of Bearing Types on Seismic Responses of Linyi Huanghe River Bridge. Bridge Construction 51(3):85–92
Zhang D, Zhang Y, Dasari A, Tan KH, Weng Y (2021c) Effect of spatial distribution of polymer fibers on preventing spalling of UHPC at high temperatures. Cem Concr Res 140:106281
Zhang F, Shen J, Liu J (2021d) Effect of encased concrete on section temperature gradient of corrugated steel web box girder. Adv Struct Eng 24(11):2321–2335
Zhang F, Yan D, Chen C (2021e) Parameter sensitivity analysis of the long-span composite girder cable-stayed bridge in the finished bridge state. Journal of Transport Science and Engineering 37(2):91–97
Zhang G, Han Q, Xu K, Du X, He W (2021f) Experimental investigation of seismic behavior of UHPC-filled socket precast bridge column-foundation connection with shear keys. Eng Struct 228:111527
Zhang G, Song C, Li X, He S, Huang Q (2021g) Fire performance of continuous steel-concrete composite bridge girders. KSCE J Civ Eng 25(3):973–984
Zhang H, Li Z, Chen G, Reven A, Scharfenberg B, Ou J (2021h) UAV-based smart rock localization for bridge scour monitoring. J Civ Struct Heal Monit 11(2):301–313
Zhang J, Hu X, Wu J, Lim YM, Gong S, Liu R (2021i) Shear behavior of headed stud connectors in steel-MPC based high strength concrete composite beams. Eng Struct 249:113302
Zhang J, Li S, Peng H (2021j) Experimental investigation of multiscale hybrid fibres on the mechanical properties of high-performance concrete. Constr Build Mater 299:123895
Zhang J, Wei K, Qin J (2021k) Resilience and economic loss assessment of highway bridges in deep reservoir under near-fault ground motions. J Bridg Eng 26(3):04021007
Zhang L, Zheng Y, Yu Y, Hu S, Wu Z, Di B, Guo Y, Li M (2021m) Structural performance evaluation of ECC link slabs reinforced with FRP bars for jointless bridge decks. Constr Build Mater 304:124462
Zhang M, Tang Z, Yun CB, Sui X, Chen J, Duan Y (2021n) Bolt looseness detection using SH guided wave and wave energy transmission. Smart Mater Struct 30(10):105015
Zhang N, Gu Q, Dong Y, Qian J, Zheng Y (2021o) Seismic performance of bridges with ECC-reinforced piers. Soil Dyn Earthq Eng 146:106753
Zhang R, Hu P, Li X, Wei D, Dai Q (2021p) Shear Behavior of Reinforced Concrete Composite Beams Without Stirrups Using U-shaped UHPC Permanent Formwork. China Journal of Highway and Transport 34(8):145–156
Zhang W, Liu Z, Liu Z (2021q) Aesthetics and Torsional Rigidity Improvements of a Triple-Cable Suspension Bridge by Uniform Distribution of Dead Loads to Three Cables in the Transverse Direction. J Bridg Eng 26(11):04021083
Zhang W, Lu X, Wang Z, Liu Z (2021r) Effect of the main cable bending stiffness on flexural and torsional vibrations of suspension bridges: Analytical approach. Eng Struct 240:112393
Zhang W, Yang C, and, (2021s) J Chang "cable Shape and Construction Parameters of Triple-Tower Double-Cable Suspension Bridge with Two Asymmetrical Main Spans" Journal of Bridge Engineering 26(2):04020127
Zhang X, Cao Z, Kong D, Liu Z, Hao C (2021u) Vibro-acoustic Characteristics and Influence Factors of a Steel Box Girder. China Journal of Highway and Transport 34(11):142
Zhang X, Cao Z, Ruan L, Li X, Li X (2021v) Reduction of vibration and noise in rail transit steel bridges using elastomer mats: Numerical analysis and experimental validation. Proceedings of the Institution of Mechanical Engineers, Part f: Journal of Rail and Rapid Transit 235(2):248–261
Zhang Y, Zheng K, Zhu J, Lei M, Feng X (2021x) Research on corrosion and fatigue performance of weathering steel and High-Performance steel for bridges. Constr Build Mater 289:123108
Zhang Z, Song C, Li X, Lan R (2021y) Comparative Study on the Small Radius Curved Bridge and Simplified Models by Shaking Table Tests. J Bridg Eng 26(7):04021039
Zhang J, Wei K, Li J (2022) Integrated assessment of the hydrodynamic added mass of the deep-water pile-cap foundation considering pile group-pile cap interaction. Ocean Eng 244:110418
Zhang, C., J. Lu, P. Wang, Z. Lai, H. Jia, and C. Wu. (2021b) Seismic fragility analysis of sea-crossing continuous rigid frame bridges based on fuzzy failure. Structures, 120–134. Elsevier.
Zhang, K., T. Qi, Z. Zhu, and X. Xue. (2021l) Study on reinforcement of fabricated hollow slab bidge by polyurethane-cement composite(PUC). Stavební obzor-Civil Eng J 30(2):393–408
Zhang, W., C. Yang, J. Chang, D. Li, and Z. Liu. (2021t) Gravity stiffness of a three-tower suspension bridge: Analytical solution via double-span bridge reduction to a single-span one with elastic constraints. 2198–2207. Elsevier.
Zhang Y, Zheng K, Zhu J, Lei M, Feng X (2021w) "Research on corrosion and fatigue performance of weathering steel and High-Performance steel for bridges." Construction and Building Materials, 289:123108. Elsevier.
Zhao G (1984) Causes and Reliability Analysis of Cracking in Concrete Structures. J Dalian Univ Tech 3:21–27
Zhao C, Zheng J, Sang T, Wang L, Yi Q, Wang P (2021a) Computational analysis of phononic crystal vibration isolators via FEM coupled with the acoustic black hole effect to attenuate railway-induced vibration. Constr Build Mater 283:122802
Zhao Q, Huang G, Xu C, Peng Y (2021c) Push-Out Behavior of Short Headed Stud Connectors in Steel-Ultra High Performance Concrete Composite Deck. KSCE J Civ Eng 25(7):2640–2650

Zhao, J., Y. Lin, X. Li, and Q. Meng. (2021b) Experimental study on the cyclic behavior of reinforced concrete bridge piers with non-uniform corrosion. Structures, 999–1006. Elsevier.
Zheng J, Li X, Bi R, Zhang X, He H, Hu Z (2021a) Structure-borne noise characteristics of fully-enclosed sound barriers on high-speed railway bridges. Journal of Traffic and Transportation Engineering 21(3):179–192
Zheng J, Liu D, Li X, Bi R, Gong Z, Hu Z (2021b) Experimental and Numerical Research on Noise Reduction Performance of Fully Enclosed Sound Barriers on High-speed Railway Bridges. China Journal of Highway and Transport 34(4):152
Zheng W, Wang H, Hao H, Bi K (2021c) Superelastic CuAlBe wire-based sliding lead rubber bearings for seismic isolation of bridges in cold regions. Eng Struct 247:113102
Zhong, C., R. Shen, and H. Wang. (2021) "Research on ultimate bearing capacity state and structure optimization of main cable saddle. 28–40. Elsevier.
Zhou L, Yang S (2021) Investigation on crack propagation in band-like rust layers on weathering steel. Constr Build Mater 281:122564
Zhou Y, Xia Y, Chen B, Fujino Y (2020) Analytical solution to temperature-induced deformation of suspension bridges. Mech Syst Signal Process 139:106568
Zhou J, Zhang S, Zhang H (2021b) Research progress of magnetic-based methods in hidden bridge disease detection. Chin Civil Eng J 54(11):1–10
Zhou L, Barbato M, Ye A (2021c) Experimental Investigation of Postearthquake Vertical Load-Carrying Capacity of Scoured Reinforced Concrete Pile Group Bridge Foundations. J Bridg Eng 26(12):04021091
Zhou M, Li P, Zhang Y (2021e) Finite beam segment analysis method for composite box girder with corrugated steel webs based on generalized displacement. Journal of Southeast University (natural Science Edition) 51(5):747–753
Zhou SC, Demartino C, Xu JJ, Xiao Y (2021f) Effectiveness of CFRP seismic-retrofit of circular RC bridge piers under vehicular lateral impact loading. Eng Struct 243:112602
Zhou X, Men P, Di J, Qin F (2021g) Experimental investigation of the vertical shear performance of steel–concrete composite girders under negative moment. Eng Struct 228:111487
Zhou Y, Uy B, Wang J, Li D, Huang Z, Liu X (2021h) Behaviour and design of stainless steel-concrete composite beams. J Constr Steel Res 185:106863
Zhou J, Li Y, Zhang H, Xia R, Yang W (2021a) Two point corrosion test study of steel strands based on spontaneous magnetic flux leakage detection". J Chongqing Jiaotong Univ (Natural Sci) 40(7):74–81
Zhou, M., Y. Chen, X. Su, and L. An. (2021d) Mechanical performance of a beam with corrugated steel webs inspired by the forewing of Allomyrina dichotoma. Structures, 741–750. Elsevier.
Zhu J, Wang Y (2021) Feature Selection and Deep Learning for Deterioration Prediction of the Bridges. J Perform Constr Facil 35(6):04021078
Zhu Y, Zhu J (2021) Distortion of steel tub-girder with top flange bracing considering warping restraint effect. J Constr Steel Res 187:106954
Zhu J, Guo X, Kang J, Duan M, Wang Y (2021a) Experimental Investigation of Flexural Behavior of Steel–UHPC Composite Beam with Waffle-Slab System. J Bridg Eng 26(4):04021011
Zhu J, Zhang Q, Xu F, Liu L, Sheng X (2021c) Review on aerodynamic noise research of high-speed train. Journal of Traffic and Transportation Engineering 21(3):39–56
Zhu L, Su RK-L, Huo J-X, Wang G-M (2021d) Test of the long-term behavior of curved steel–concrete composite box beams: case study. J Bridg Eng 26(9):05021009
Zhu Y, Hussein H, Kumar A, Chen G (2021e) A review: Material and structural properties of UHPC at elevated temperatures or fire conditions. Cement Concr Compos 123:104212
Zhu Y, Wan S, Shen K, Zhou P, Wang X (2021f) Theoretical study on the nonlinear performance of single-box multi-cell composite box-girder with corrugated steel webs under pure torsion. J Constr Steel Res 178:106487
Zhu J, Zhang Y (2021) Damage detection for bridge structures under vehicle loads based on frequency decay induced by breathing cracks. Structure and Infrastructure Engineering. pp 1–17
Zhu J, Li H, Wang S (2021b) Defect recognition for steel bridge based on convolutional neural network and transfer learning. J Chang'an Univ (Natural Sci Edition) 41(3):52–63
Zhuang L, Chen H, Ma Y, Ding R (2021) Research on Whole-Process Tensile Behavior of Headed Studs in Steel-Concrete Composite Structures. International Journal of Concrete Structures and Materials 15(1):1–25
Zou J, Yang J, Li H, Shuai C, Huang D, Jiang S (2021a) Bridge apparent damage detection based on the improved YOLO v3 in complex background. Journal of Railway Science and Engineering 18(12):3257–3266
Zou Y, Zheng K, Zhou J, Zhang Z, Li X (2021b) Mechanical behavior of perfobond connector group in steel–concrete joint of hybrid bridge. Structures 925–936. Elsevier

Publisher's Note