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State-of-the-art and annual progress of bridge engineering in 2020

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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 2020 from 16 aspects. The content consists of four major categories in 16 aspects. The first part is about the bridge structure, including concrete bridge and high-performance materials, steel bridges, composite girders. The second part is about the bridge disaster prevention and mitigation, including bridge seismic resistance, wind resistance of bridge, train-bridge coupling vibration research, bridge hydrodynamics, the durability of the concrete bridges, fatigue of steel bridge, temperature field and temperature effect of bridge; The third part is about the bridge analyses, including numerical simulation of bridge structure, box girder and cable-stayed bridge analysis theories. The last part is concerning the bridge emerging technologies, including bridge informatization and intelligent bridge, the technology in bridge structure test, bridge assessment and reinforcement, prefabricated concrete bridge structure.

Keywords: Bridge engineering, Annual Progress in 2020, Review

1 Introduction

Bridge construction is closely related to the development of human civilization and is also an important part of human civilization. It is the unremitting pursuit and dream of human beings to build bridges and overcome obstacles, making a deep chasm turned into a thoroughfare.

The construction scale and the technical level of China's bridge engineering have already reached the world's advanced level in recent decades. With the rapid development of China's economy, the society has increasingly higher construction needs for infrastructure and transportation systems, and there are continuous construction and completion of ultra-long sea-crossing bridges, high-speed railway bridges, and super-span bridges. At the same time, with the expansion and deepening of scientific research and technical application in the field of bridge engineering, new technologies, new materials, new structures, new technical theories, etc. have emerged one after another, and the level of technical application and theory of bridge construction has reached an unprecedented height. With the progress of the construction progress, the span demand of the bridge is increasing; the functional requirements are getting higher and higher, such as all-weather opening to traffic, road-rail dual-use, high-speed railway; the construction conditions and operating environment are becoming more and more severe, such as typhoon, fracture zone, Plateau, strong earthquake, tsunami, etc. All these provide a wealth of research topics and design challenges for bridge design and scientific research personnel.

In the past year, China's bridge construction has produced fruitful development achievements in many fields. In order to achieve more outstanding achievements in the future, it is essential to analyze, summarize and forecast the progress of bridge research in the past year. This paper introduces the progress of bridges in 2020, which consists of four major categories in 16 aspects. The first part is about the bridge structure, including concrete bridge and high-performance materials, steel bridges and composite girders, which are the content of section 1–3 of this study. The second part mainly is about the bridge disaster prevention and mitigation, including bridge seismic resistance, wind resistance of bridge, train-bridge coupling vibration research, bridge hydrodynamics, the durability of the concrete bridges, fatigue of steel bridge, temperature field and temperature effect of bridge, which are the content of section 4–10 of this study. The third part is concerning the bridge analyses, including numerical simulation of bridge structure, box girder and cable-stayed bridge analysis theories, which are the content of section 11–12 of this study. The last part introduces the bridge emerging technologies, including bridge informatization and intelligent bridge, the technology in bridge structure test, bridge assessment and reinforcement and prefabricated concrete bridge structure, which are the content of section 13–16 of this study.

2 Advances in concrete bridges and high-performance materials

Concrete bridge is an earlier development field of bridge engineering, so compared with other bridge types, its development is more mature. But the maturity of technology does not mean that it is out of date. There are still many researches on concrete bridge and its new materials published in 2020.

2.1 Concrete bridge

2.1.1 Mechanical properties of concrete bridge

In recent years, although the research on the mechanical properties of concrete bridges, especially the overall mechanical properties, tends to be mature, some scholars are still making continuous efforts to make new achievements in prestressed concrete bridges, concrete arch bridges, locally stressed components of concrete bridges and seismic resistance of concrete bridges. In the aspect of prestressed concrete continuous beam bridge, Breccolotti (2020) pointed out that the stress loss caused by the corrosion of prestressing tendon is the main reason for the collapse of corresponding bridge, and proposed a new numerical method to evaluate the influence of prestress loss on the vibration frequency of continuous prestressed concrete bridge; Terry et al.(2020) proposed a three-dimensional discrete finite element model for externally prestressed concrete bridge, and then modified the model by the previous research results. Through the analysis results of the modified model, it is concluded that the bending capacity of the beam will increase by 10% or decrease by 16.8% when the prestress is increased or decreased by 20%, and at the same time, it can also reduce the bending deformation capacity by 30.2% or increase it by 36.6%.

In the aspect of concrete arch bridge Elrehim et al. (2019) developed a technology that can optimize the genetic algorithm by using MATLAB programming platform, and compared the optimized results with the traditional results, which significantly reduced the cost. Panian and Yazdani (2020) developed a new method by using the stress intensity factor in fracture mechanics, which can accurately predict the maximum service load of plain concrete railway arch bridge and can be well applied to its safety state assessment.

In the research of concrete bridge components and local stress Kuryłowicz-Cudowska et al.(2020) accurately estimated the compressive strength of concrete bridge deck based on the methods of field temperature monitoring, numerical simulation and maturity function, and determined the actual strength of cast-in-place concrete bridge deck and the best date of prestressing. Wang et al. (2020a) studied the failure mechanism of concrete box girder bridge deck through field measurement and finite element analysis, determined three typical failure modes (bending cracking, punching failure, deck cracking and concrete crushing), and proposed corresponding reinforcement methods for different failure modes.

In the aspect of seismic and impact performance analysis of concrete bridges Farshad and Mahdi (2020) found that neglecting the soil structure interaction would lead to overestimation of the bearing capacity of the bridge and the credibility of meeting the safety state. Pang et al. (2020) established FRC piers strengthened with different fibers, analyzed their seismic vulnerability curves, and then pointed out: compared with steel fiber reinforced piers, polypropylene fiber reinforced piers perform best in dealing with bending failure and brittle failure. Jia et al. (2020d) analyzed a composite girder cable-stayed bridge by using nonlinear time history analysis method, studied its seismic response under ductile seismic system and seismic isolation system, and selected the seismic isolation system suitable for the bridge. Hájek et al. (2020) carried out the numerical evaluation research on the near-field Explosion Response of concrete fiber composite bridge deck by means of numerical simulation and experiment, and pointed out that: in the designated damage area, the energy generated by explosion is consumed by the highly heterogeneous concrete composite bridge deck through delamination.

It is suggested that the research on spatial shear behavior of concrete structure should be improved and the discrete element simulation method should be further developed, so as to reduce the transition dependence on the finite element simulation in the current research and improve the calculation accuracy.

2.1.2 Operation and maintenance of concrete bridge

Konen et al. (2020) found that in service concrete bridge members, chloride content in unit mass concrete was the main parameter leading to reinforcement corrosion and nonlinear degradation of concrete performance, and pointed out the key areas of corrosion degradation. Srikanth and Arockiasamy (2020) compared different bridge deterioration models and pointed out the advantages and disadvantages of each model.

In terms of time-varying performance research Wang et al. (2020k) based on the elastic similarity theory and the calculation formula of creep deformation of concrete structure, the concept of the adjustment coefficient of creep similarity constant was proposed, and the adjustment coefficient formula of creep similarity constant of plain concrete column, reinforced concrete column, concrete-filled steel tubular column, steel bar and prestressed concrete beam was derived. Yuan et al. (2019) has carried out extreme value modeling, non-stationary resistance deterioration process modeling and model modification of concrete bridge by considering the time course of the load of nonstationary vehicles and the nonstationary process of resistance degradation, and then proposed a method of time-varying reliability evaluation.

In terms of operation and maintenance of concrete bridges, Yazdani and Azimi (2020) pointed out that the dynamic performance of operating bridges under the action of high-speed trains was affected by the track span, vehicle speed, material stiffness, train carriage distribution and wheelbase. Zhou et al. (2021a) proposed a multi-level evaluation method based on deflection to evaluate the operation state of prestressed continuous rigid frame bridge.

2.2 High-performance materials

The progress in high-performance concrete will be introduced from the following three aspects: high mechanical properties, green environmental protection and intelligence.

2.2.1 Ultra-high performance concrete (UHPC)

As for the application of UHPC in bridge engineering, Shao et al. (2020) proposed using short steel bars as a new type of connector for steel-ultrathin UHPC composite bridge decks, and studied the shear performance of the connector through static push-out test and fatigue push-out test. Li et al. (2020e, 2021d) proposed to apply UHPC to the bent cap and carried out model test and finite element simulation in combination with the actual project. The results illustrated that the new fully prefabricated prestressed UHPC bent cap had good deformation capacity and anti-crack behavior. Sturm et al. (2020) conducted four point bending tests on UHPFRC beams with steel tendons and CFRP tendons. The results showed that the beams with CFRP tendons had greater bearing capacity under large deformation, smaller main crack width before yielding, but lower cracking stiffness. Liu et al. (2020j) and Zhang et al. (2020h) studied the mechanical properties of steel-UHPC composite beams in the negative bending moment zone, and the results showed that UHPC could increase the cracking load in the negative bending moment zone, reduce the crack spacing, and inhibit the development of cracks.

2.2.2 Green concrete

Recycled aggregate concrete (RAC) and geopolymer concrete (GPC) are the two main directions for the development of green concrete. Xiao et al. (2020) believed that the current RAC met construction requirements. However, considering the shortcomings in the seismic design, optimization of key parameters in the analysis process, including mechanical parameters, constitutive models, and damping ratios, was proposed.

Significant progress has also been made in the research on geopolymer concrete. Liu et al. (2020l) found that it was possible to prepare UHPC by using geopolymer with slag and fly ash as the precursor. By incorporating silica fume and steel fibers, the compressive strength of ultra-high performance geopolymer concrete (UHPGC) reached more than 150 MPa.

Wu et al. (2020d) carried out a research on the mechanical properties of GPC reinforced beams and found that the design specifications of ordinary concrete beams underestimated the load-bearing capacity of GPC beams. GPC reinforced components have good mechanical properties.

Sun et al. (2020b) found that the workability and mechanical properties of geopolymers met the requirements of 3D printing materials by testing the plastic viscosity and yield stress. Panda et al. (2020) modified its properties by incorporating nano-clay and produced 3D printing objects, which verified the feasibility of geopolymers for 3D printing.

In summary, while the mechanical properties and durability of geopolymers are constantly improved, they are also penetrating into other high-performance concrete fields, such as: UHPC, ECC, self-compacting concrete, 3D printing concrete, recycled aggregate concrete, etc.

2.2.3 Intelligent materials

The characteristics of intelligent concrete materials include self-diagnosis, self-regulation, self-repair and other functions, which is the advanced stage of the development of traditional concrete materials.

Shape memory alloy (SMA) can be used for seismic damage control. Zhang et al. (2020u) proposed a swing-self-resetting (SCR) pier using SMA cables. The study found that due to the super elasticity of the SMA cable, the pier specimen hardly suffered damage within 4% drift. In addition, SMA fiber can be mixed with concrete to prepare self-repair concrete by using its shape memory effect.

Research on self-healing concrete is also gradually emerging. Mondal et al. (2020) prepared self-healing concrete with a kind of radiodurans as a self-healing agent, leading to effective crack-healing at 4 ± 1 °C.

3 Advances in steel bridges

3.1 Development of steel bridges in China

3.1.1 The longest arch bridge in the world: the 3rd bridge at Pingnan

In the historically unusual year of 2020, a list of crucial achievements has been made by the diligent bridge community in China. In December 2020, the 3rd Bridge at Pingnan was completed and opened to traffic in Guangxi Province, China, as shown in Fig. 1. The bridge has a main span of 560 m (575 m in the total length of the arch), stepped as the world longest arch bridge after erected. The hung deck is 36.5 m in width, carrying 4 lanes, 2 bikeways and 2 sidewalks in two directions. The steel tube of the arch is

Fig. 1 Pingnan the 3rd Bridge in Guangxi Province

filled with the high-strength concrete C70, and a total of 15,000 tons of structural steel and been utilised (Du et al. 2019). Since then, all the top five longest arch bridges are in China, including the Chongqing Chaotianmen Yangtze River Bridge (552 m) built in

2009, Shanghai Lupu Bridge (550 m) built in 2003, Sichuan Hejiang Bosideng Bridge (530 m) built in 2013 and Hubei Zigui Yangtze River Bridge (519 m) built in 2019.

3.1.2 The longest road-highspeed-rail suspension bridge in the world: Wufengshan Yangtze bridge

Also, in December 2020, the Jiangsu Wufengshan Yangtze Bridge is erected and opened, as shown in Fig. 2. The bridge is a road-rail suspension bridge, with a main span of

Fig. 2 Wufengshan Yangtze River Bridge

1092 m. The hanger of the bridge carries two decks, including the upper deck of 8 road lanes and the lower deck of 4 highspeed railways. The road lane has a design speed of 100 kph, while the opened two railways carry the Lianzhen highspeed rail that operates at a design speed of 250 kph. Meanwhile, the remain 2 railways are reserved for future usage, with a design speed of 200 kph. The Wufengshan Bridge is first road-rail suspension bridge in China, as well as the world first road-rail suspension bridge with the highest operational speed and heaviest vehicle loads (Tang et al. 2020). In the full test before opening, a world record of the operational speed of 275 kph has been achieved for the railway suspension bridge.

3.1.3 The first road-rail strait crossing in China and the longest one in the world: the Pingtan Strait road-rail crossing

The Pingtan Strait Road-rail Crossing carries the Pingtan railway and Changping express, starting at Songxia Town in Changle District in Fuzhou City and passing the Island Reyu, Changyu, Xiaolian, Dalian until its end at Island Pingtan. The crossing is 16.3 km in total, in which 9.2 km is carried on rail-road bridges. In October and December 2020, the roadway and railway of the bridge are opened to traffic, respectively, as shown in Fig. 3. At the time of erection, the crossing is the 1st road-rail strait crossing in China and the longest one in the world (Mei et al. 2020b).

3.2 Novel and special materials and configurations in steel bridges

3.2.1 The application of smart iron-based shape memory alloy

Izadi et al. (2019) investigated the application of smart iron-based shape memory alloy (FE-SMA) in connections of steel bridges. The double angle steel-based connection in railway riveted steel bridge is highly prone to fatigue cracking due to the lack of stiffness. The existing repair approaches could not solve the fatigue cracking issue of the above riveted connection ideally. The Fe-SMA has the effect of shape memory, which enables the easy application of prestress on the connection of steel bridges. Thus, the test toolkit was designed by Mohammadreza, as shown in Fig. 4, aiming at the static and fatigue test of double angle steel connection reinforced by the SMA. The result suggests a notable improvement in the fatigue life of the above connection after strengthened by Fe-SMA strips. This work is a constructive trial application of SMA materials in bridges.

3.2.2 The application of stainless steel

Stainless steel has a prominent trait of anti-corrosion ability, improving structural safety and durability as well as the efficiency in material recycling. For years, a part of developed contrived has managed to develop small-scale roadway, railway and pedestrian bridges using stainless steels, as shown in Fig. 5. Although the initial cost of stainless-steel bridges is about 300% higher than the one using the carbon steel, the erected bridge shows advantages in both structural performance and appearance. Moreover, the maintenance cost during the bridge service life could be effectively saved since the stainless steel is coating-free. According to the relevant study (Kere and Huang 2019), the stainless-steel bridge has a comparable economy in the life-cycle design of bridges with specified structures or usages. Thus, the detailed provision has been included in the Eurocode 3 (EN 1993-1-4) as 'supplement about stainless steels', respecting the requirement on

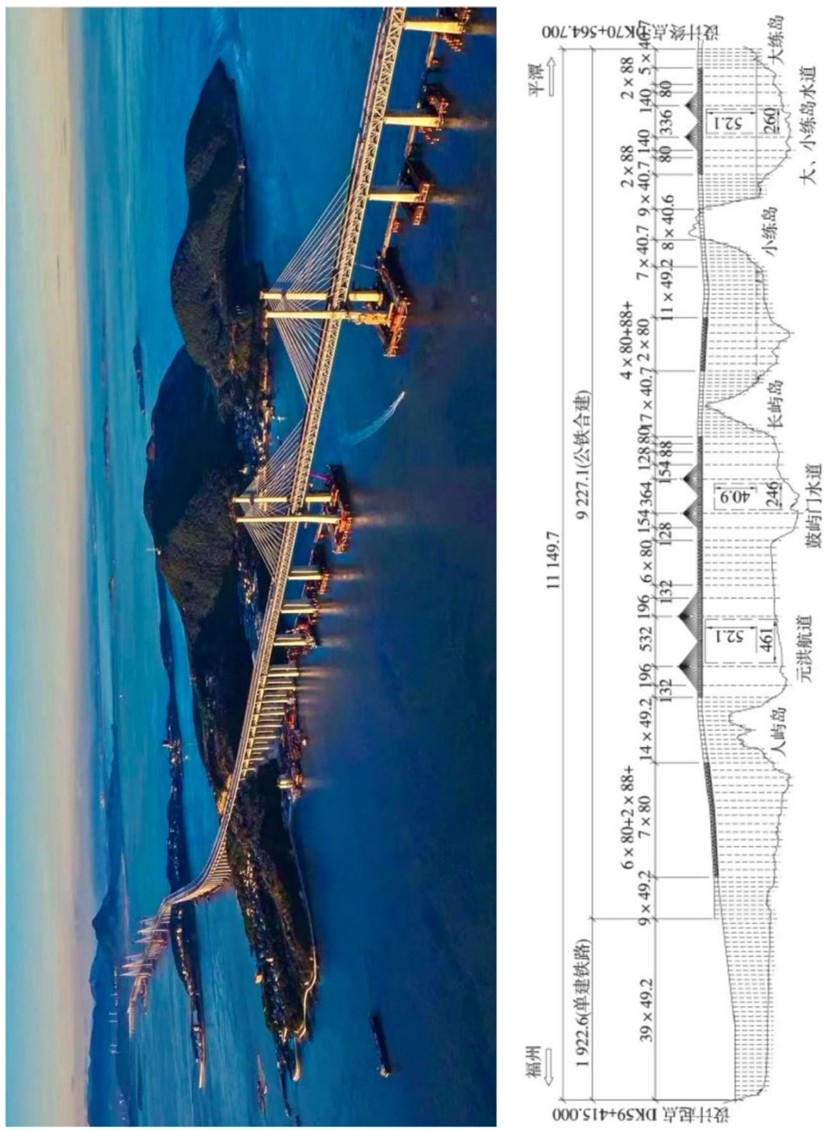

Fig. 3 Pingtan Strait Crossing

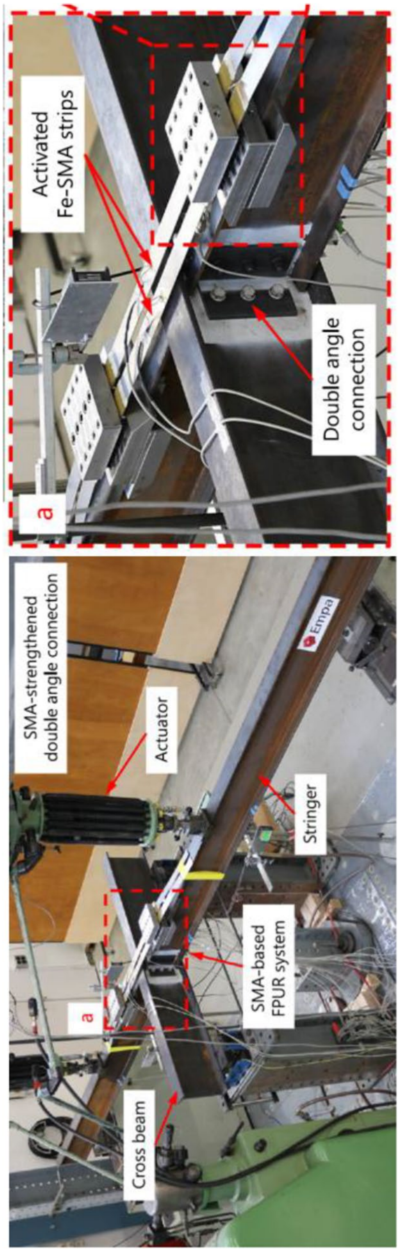

Fig. 4 High-cycle fatigue test of steel-based shape memory alloy lath-strengthened longitudinal and transverse beam web angle steel connections

Fig. 5 Some highways, railways and pedestrian stainless-steel bridges (or some components) at home and abroad

parental materials, bolt connections and welds in the stainless steel. The similar provision has also been included in the American specification ASIC.

3.2.3 The research and application of weathering steel and high-performance steel

An alternative to the stainless steel is the weathering steel, which shows a much lower material cost. Under the environmental aggression, a dense rust layer would be formed on the outer surface of the weathering steel, which delays further corrosion. The weathering steel also shows desired anti-corrosion performance. As a result, the repeated coating efforts could be avoided during the bridge service, which also effectively reduces the maintenance cost. The high-performance steel is an extension of the weathering steel, which has high strength, good weldability, ductility and toughness apart from the anti-corrosion ability. In recent years, people have already seen a series of engineering applications of weathering steels in bridges in China (Zheng et al. 2020c). Zheng et al. (2019) combined the electrochemistry and fracture mechanics to established the corrosion-fatigue coupled prediction model of weathering steels, as shown in Fig. 6. According to the model, the corrosion-fatigue process could be divided into two stages, including the crack initiation and crack growth. In the initiation stage, the crack starts from the corrosion pit under the effect environmental aggression. Once the crack reaches the critical size, the fatigue effect begins to impose prominent influence on the crack growth. As a result, the corrosion and fatigue will compete in terms of the crack growth rate until the fatigue effect becomes the primary one. After that, the crack keeps growing under the fatigue until failure.

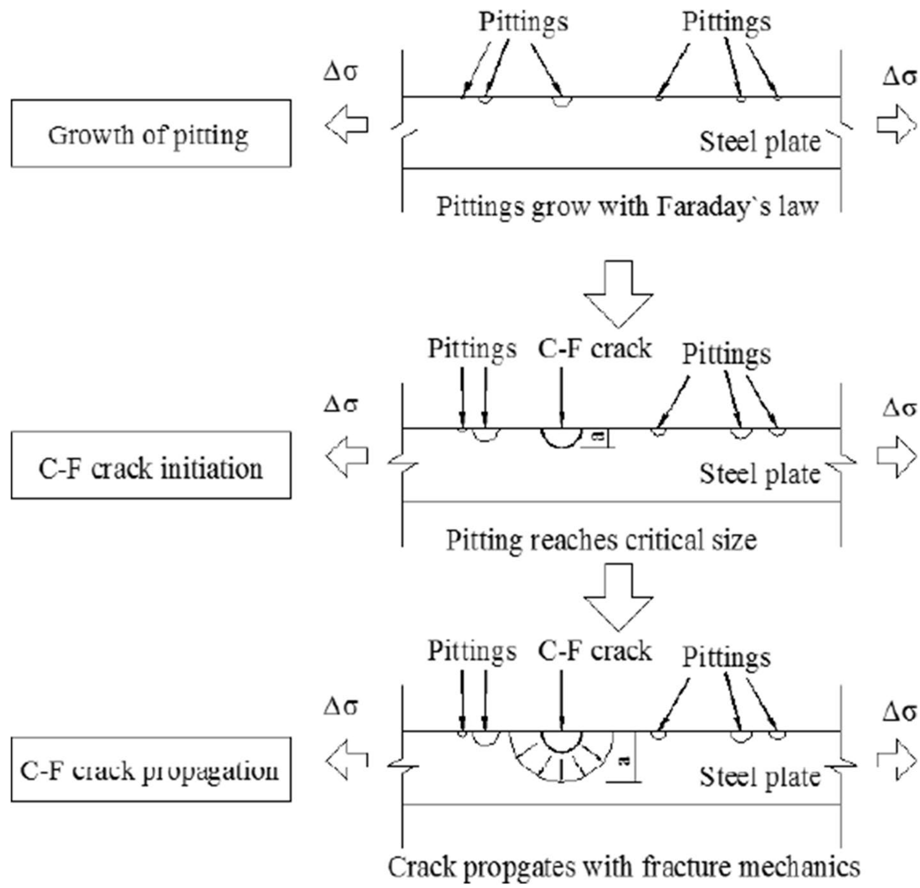

Fig. 6 Corrosion fatigue process of weathering steel

3.2.4 The application of aluminium alloy

The aluminium alloy has a promising future of application in some special bridges due to its advantage of lightweight, high strength-to-weight ratio, good anti-corrosion ability and easy recyclability. The Smithfield Bridge, constructed in the US in 1940s, is the world 1st bridge fabricated by aluminium alloys. In China, the aluminium alloy is for the 1st time hired in 2006 to develop the Zhonghe Pedestrian flyover in Qingchun Road, Hangzhou City, Zhejiang Province. However, the study is still lacking over aluminium alloy bridges.

3.2.5 The research and application of I-shaped beam formed by butt welding of hot-rolled ribbed flange and steel plate

Hot-rolled I-shaped beam has been extensively applied due to its convenient production and usability. However, limit exists on its height and flange width due to limitations in the hot-rolled technology, which is ground truth all over the world. Although the welded I-shaped beam could be used, it shows increased manufacturing cost due to the requirement of double-sided welding. On this basis, a novel type of efficient I-shaped beam, as shown in Fig. 7, is developed by the group headed by Prof Kaifeng Zheng at the Southwest Jiaotong University and Liaoning Zizhu Group Co. Ltd. The efficient I-shaped

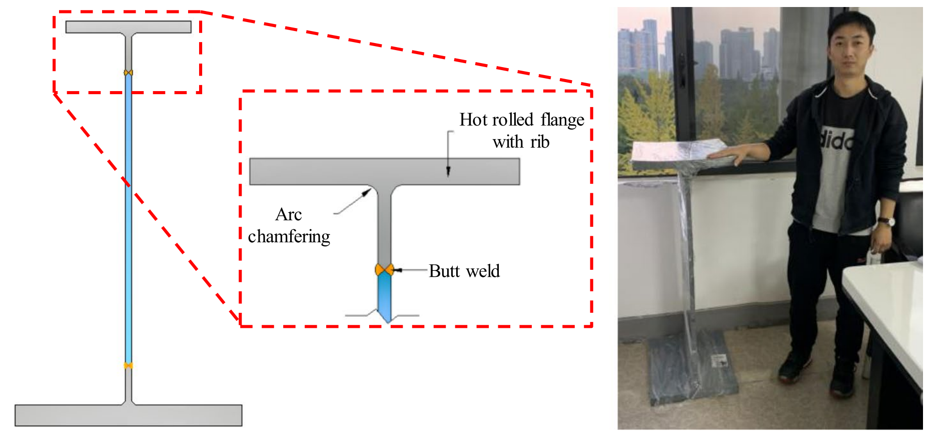

Fig. 7 I-shaped beam formed by butt welding of hot-rolled ribbed flange and steel plate

beam consists of two T-shaped hot-rolled beam and a plate beam, which are connected through full-penetration welding. Compared with traditional welded I-shaped beam, the efficient one only requires the butt welds instead of the fillet welds. According to preliminary study, the efficient I-shaped beam shows good performance and economic costs, which enables its promising application in bridges.

3.3 Orthotropic steel deck (OSD)

3.3.1 The research and application of hot-casted OSD based on the spherical graphite cast iron

Hironobu et al. (2017, 2018) investigated a novel type of hot-casted OSD based on the spherical graphite cast iron (SGCI), as shown in Fig. 8. Compared with the classical cast iron, the SGCI shows improved material performance, which is comparable to the structural steel. By using the SGCI, the OSD could be casted as an integrated component without the complicated welding process. As a result, the welding defect and residual stress would be avoided. According to the requirement on the mechanical behaviour, the SGCI-based OSD could be further optimized in terms of the height, width and transition angle between components. On this basis, the stress concentration in the transition area could be mitigated, which further enhance the fatigue performance of SCGI-based OSD. According to the fatigue test data, the SCGI-based OSD shows no fatigue crack after loaded to 2,000,000 cycles under a stress range of 140 MPa. Currently, the SCGI-based OSD has been applied in several bridges in Japan.

3.3.2 The research of OSD using corrugated core sandwich panel

Nilsson et al. carried out a series of studies on the OSD using corrugated core sandwich panel (CCSP) (Nilsson et al. 2017). As shown in Fig. 9, the CCSP consists of an 8 mm-thick top plate, a 5 mm-thick bottom plate and a 6 mm-thick corrugated core. The above three parts are connected as an integrated panel via laser welding, which results in no obvious welding defect and residual stress. According to the test data, the OSD using CCSP shows an enhanced performance in both the fatigue and static behaviour.

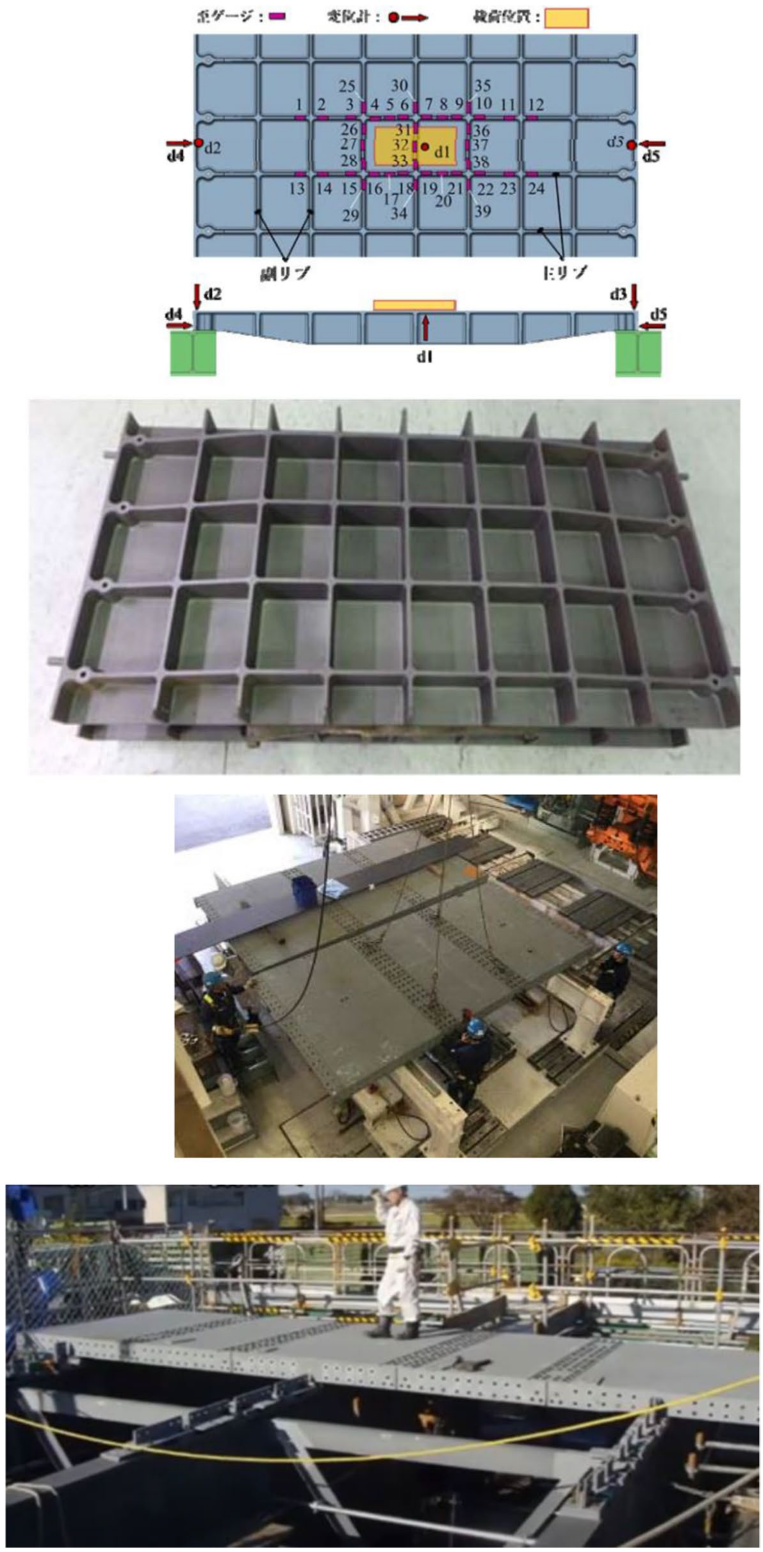

Fig. 8 Test and use of SGCI-based steel bridge deck

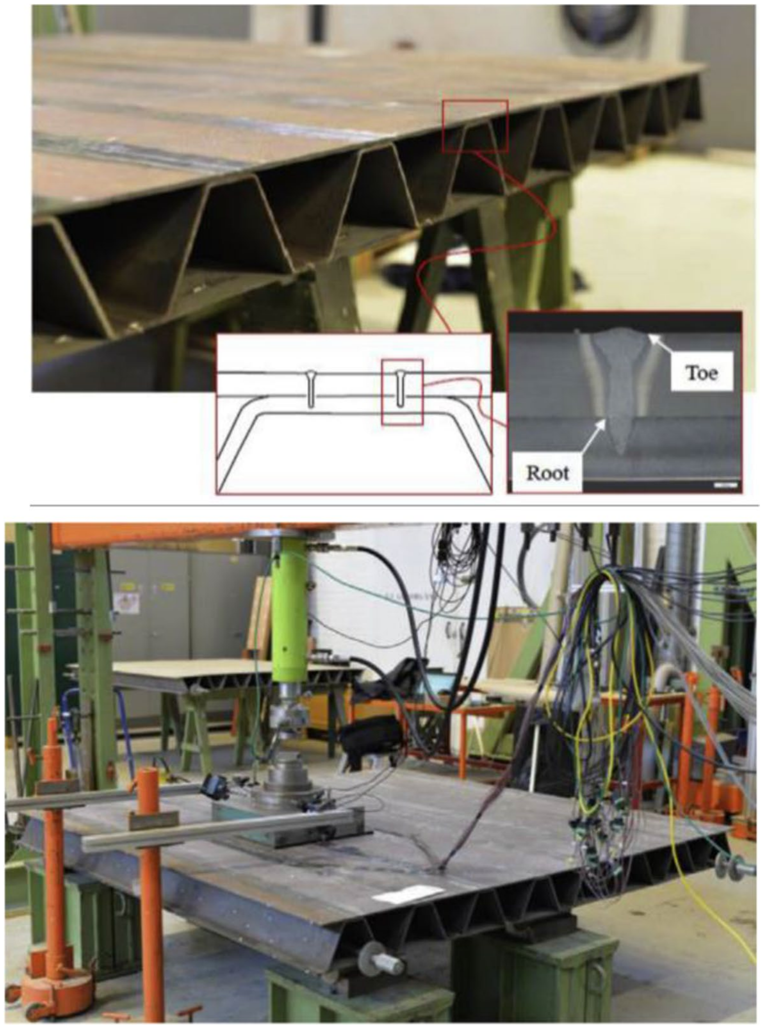

Fig. 9 Corrugated core sandwich panel (CCSP) and fatigue test

3.3.3 The research of high fatigue resistance OSD

Zhang et al. (2019) claimed that the fatigue performance of OSDs is controlled by the governing fatigue cracking model among the multiple cracking models. On this basis, the high fatigue resistance OSD (LI et al. 2019) is proposed, which has the configuration innovation at both the rib-to-deck and rib-to-floor beam welded connections, as shown in Fig. 10. The study (Zhang et al. 2020l; n; Zhu et al. 2017) shows a notable reduction in the accumulated fatigue damage of the governing fatigue cracking in the high fatigue resistance OSD, suggesting a notably improved fatigue performance over the traditional OSD.

Zhu et al. (2017) conducted the static and fatigue tests on the full-scale OSD specimen with the inner diagram inside the U-rib. According to the test data, the stress concentration is notably mitigated by using the inner diagram, which in turn prolongs the fatigue life. Zheng et al. carried out a systematic fatigue test, as shown in Fig. 11, to investigate the influence of the post-weld heat treatment (PWHT) and the inner diagram on the

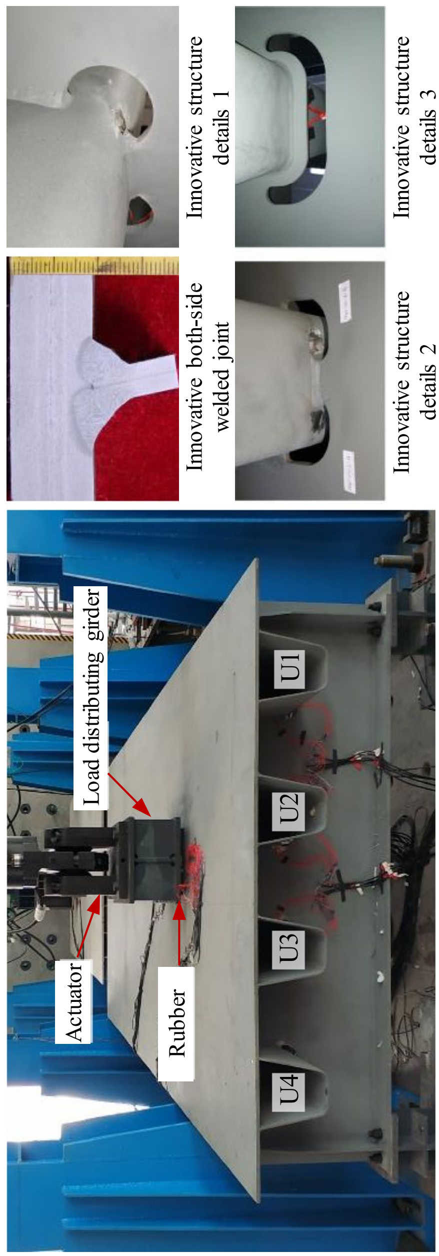

Fig. 10 High fatigue resistance OSD

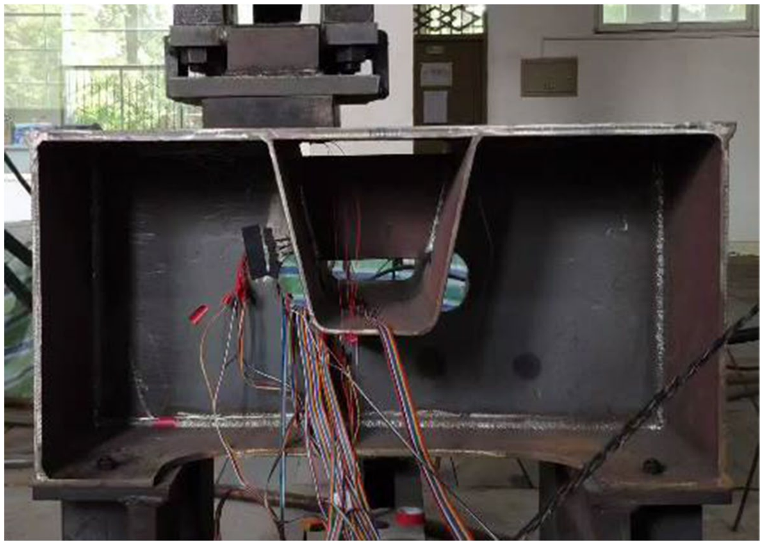

Fig. 11 Fatigue test of OSDs with PHWT and inner diaphragms

fatigue performance of welded joints in OSDs. A total of 12 specimens have been tested, suggesting the notable improvement in the fatigue strength of rib-to-floor joint by the application of PWTH and inner diagrams.

Another notable innovation in steel bridge decks is the application of the composite deck, consisting of a light deck system and a thin-layer of ultra-high-performance concrete (UHPC). Zhang et al. (2020o) proposed the novel steel-UHPC composite deck with large-size U-ribs, as shown in Fig. 12. A series of theoretical and experimental studies have been conducted on the structural optimization, static and fatigue behaviour of crucial components, fatigue failure mechanism. As a result, the fatigue failure model under different structural systems has been revealed, while the fatigue evaluation approach is preliminarily established considering the steel-concrete coupled deterioration effect.

4 Advances in composite girders

Steel-concrete composite bridge, one of the sustainable engineering structures, has excellent technical, economic and social results, and is increasingly popular in the bridge engineering. The steel-concrete composite structure has been widely used in many fields of bridge engineering, because of the reasonable load transfer, the economic efficiency, and the ease of construction.

4.1 Shear connectors

General research on shear connectors contains push-out tests and finite element simulations, which may be the main research methods. In the past, the shear performance of connectors has been studied deeply. Nowadays, researchers pay more attention to the actual applied scenarios of shear connectors and the use of new materials.

Push-out tests with high strength steel and UHPC are conducted to study shear performance of connectors (Tong et al. 2020a). Short channel connectors in the thin deck with UHPC are studied (Zhao et al. 2019). Group studs effects of rubber-covered shear

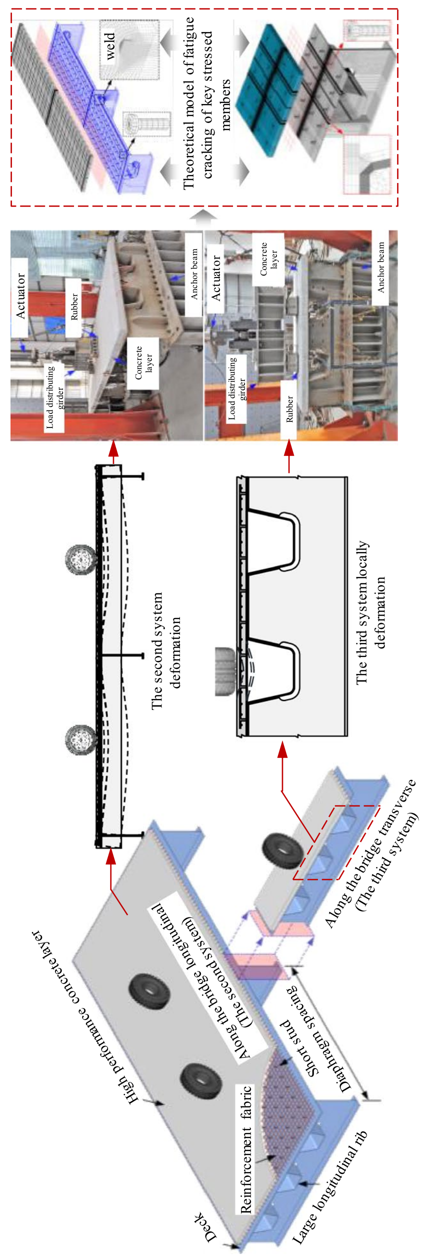

Fig. 12 Novel steel-UHPC composite deck with large-size U-ribs

studs are studied (Huang et al. 2020b). The effects on shear connectors with tension stress by the form of the stiffener and the cross beam are studied (Liu et al. 2020n). The ultimate capacity formulas of shear studs with coupled tension-shear stress are studied (An et al. 2020). Push-out tests of rubber-covered shear studs with different height of rubber are conducted and the slip equations and S-N curves for rubber-covered shear studs are established (Xu et al. 2020e). Rubber-sleeved Stud connectors, RSS, in cable tower are studied through section model tests and FE simulations. The slips and stress of the concrete tower with different distribution of RSS are studied (Zhuang et al. 2020).

PBL shear connectors are another form of general connectors, which can be applied in different scenarios, such as the steel-concrete joint, the composite beam with corrugated steel webs. Push-out tests of PBL shear connectors with exterior compression are studied, such as the simulation of the pylon anchorage area in the cable tower (Zhan et al. 2020b). Out-of-plane shear performance of PBL are received attention to study the lateral moment state (Liu et al. 2020m). The performance of PBL connectors with or without steel channel constraints is studied to simulate the real force transfer model of the steel-concrete joints of cable-stayed bridges, and the shear mode (He et al. 2020c). The stress transmission and failure modes of steel-concrete joints, as well as the influence of steel-concrete friction, are analyzed (Zou et al. 2020b).

Compared with shear studs, bolted shear connectors are also widely concerned, and have advantages of more flexible and faster construction. Ten push-out tests are conducted to study the distribution of multiple connectors, the spacing of bolted shear connectors and shear strength of connectors under reinforcement measures (Yang et al. 2020d). The stiffness, the ultimate strength and the ductility of the bolted shear connectors are studied through static load tests, and the S-N curve of the bolted shear connectors is obtained through the high-cycle fatigue test, as well as failure modes (Hossain et al. 2020a). The effects of failure mode and combined stiffness of composite girders, the strain distribution near the opening, and the bolt tolerance are analyzed (Li et al. 2020f).

The durability and degradation performance of the connector is also one of the concerned hotspots. Shear performance of studs under low temperature (Xie 2020), group effects under the low-cycle load (Zhao et al. 2020a), the residual capacity considering original defects (Rong et al. 2013) and corrosion(Zhang et al. 2020f), is studied, which is helpful to the study of the long-term performance of composite beams, as well as the establishment of full-life design and damage prediction.

In general, shear studs, as the most common shear connectors, have received much attention, and improved connectors under different application conditions are gradually being studied. The performance of shear connectors under actual composite stress state, not just the ability of pure shear resistance, is much concerned.

4.2 Steel-concrete composite girders

In order to avoid complex three-dimension model, researchers put forward with several beam element models and simplified equations to explore the short term and long-term performance of composite girders. One type of new composite beam element is proposed with the coupled multi-axial constitutive relationship and the new stability criterion for materials (Das and Ayoub 2020). One-dimensional finite element model is established by using the higher-order beam theory (Uddin et al. 2020) and time-varying finite element model is formed by using general beam theory to study the effects of concrete creep, shear lag and distortion (Henriques et al. 2020). The theoretical model with 11 degrees of freedom is built, containing two-way slips, the lateral displacement, deflections, the torsion angle and the warping angle (Zhu et al. 2020d). Static analysis method of composite beam based on the collocation method is proposed without the spatial discretization (Lin 2020b). Based on Hamilton method, one type of improved analysis method on the basic frequency of the composite box beam with corrugated steel webs is developed (Feng et al. 2019). Considering bonding, friction, the tangent slip and normal cracks in the interface, refined state of the steel-concrete interface is described by the cohesive zone model (Lin et al. 2019). The sequential linear programming algorithm is used to optimize the finite element model of steel-concrete composite beams with partial interactions (Silva et al. 2020).

The flexural performance of composite girders has always been the focus and closely related to the practical engineering demand. Simplified numerical models are established to study composite girders when the above conditions change (Kalibhat and Upadhyay 2020b). Two types of distribution of shear studs and interfaces are considered, and the interaction force between the concrete and studs is measured to obtain the shear force (Hillhouse and Prinz 2020). Three-dimensional finite element model is built to study the distribution of the moment and the shear force under static loads, and the results is compared with the Canadian highway bridge design code (Razzaq et al. 2020). The transverse reinforcement ratio, the shear connection degree, the difference effects of one row and two rows of shear connectors and the influence of studs' diameter are considered to study the longitudinal shear behavior and the failure mode (Zhang et al. 2020e).

The lateral deformation is also received much attention. Considering compression membrane effects of the deck in the composite box girder, the capacity of decks is studied (Zhu et al. 2020h). Lateral moment distribution is studied by the rigid beam method and the frame model (Kong et al. 2020). Parametric analysis about the effects of geometric parameters and the crack state of the concrete deck on the lateral moment distribution is conducted (Xiang et al. 2020a).

Two types of concrete, SFRC, ECC and two types of shear connectors, are applied in composite curved box girders and studied (Zhu et al. 2020e). Three types of composite girders, containing steel-concrete composite girders, steel-UHPC composite girders, steel-concrete-UHPC composite girders, are compared by experiments and simulations (Liu et al. 2020c). The details between the prefabricated deck and the girder are explored (Haber et al. 2020). The effects of clustered arrangement of studs in steel-UHPC composite girders on the yield load, the ultimate load and elastic stiffness are studied (Hu et al. 2020c).

In addition, other complex spatial behaviors are also studied by researchers. Twin I-shaped composite girders under symmetrical loading and asymmetrical loading are tested (Weiwei et al. 2020). The lateral buckling capacity is studied (Rossi et al. 2020). I-shaped steel-concrete composite beams subjected to bending and torsion at the same time are explored (Suzuki et al. 2020). The bending-shear-torsion combined action of the composite box girder is experimented, and the generalized Cardiff model is used (Soto et al. 2020). The structural details, including steel strength, height-depth ratio, transverse bars ratio and the arrangement of ribs, are considered (Zhu et al. 2020a, b).

The above research is mainly concentrated on I-shaped composite girders with shear studs. As for other types of composite girders, such as composite box girders with corrugated steel webs, truss composite beams and composite girders with concrete-filled steel tube, there is relatively little research. The elastic shear lag effects of corrugated steel web combined box girder with variable cross-section and the influence of bars is extremely studied (Zhou et al. 2020a). The flexural performance of the composite box girder with the concrete slab at top, trusses at bottom and corrugated webs is studied (Chen et al. 2020g). The torsion performance of composite girders with the concrete slab at top, the steel plate at bottom and corrugated webs (Zhang et al. 2020v). The composite beam with multiple longitudinal and longitudinal joints, containing channel shear connectors and I-shape steel, is studied (Arıkoğlu et al. 2020). The four-point flexure tests of the composite girder with friction-based shear connectors under cyclic loads are conducted to study the effective width, the failure mode and the crack propagation (Suwaed and Karavasilis 2020). The different asynchronous construction technology for composited girders with corrugated webs are explored and compared (He et al. 2020; Wang et al. 2020; Zhou et al. 2020j).

Because the concrete is vulnerable to cracks, one of the direct methods is to use high-performance concrete materials to improve the cracking performance of the concrete slab to improve the crack resistance. UHPC (Zhu et al. 2020g), steel fiber reinforced UHPC (Qi et al. 2020) and ECC (Fan et al. 2020a) are applied in composite girders. Two types of bolted shear connectors and shear studs in steel-UHPC composite girders are compared to study the crack-resistance performance in the negative moment zone (Zhang et al. 2020r). Experimental investigation of the vertical shear performance under negative moment are conducted (Zhou et al. 2021d) and the simplified numerical model is used to study the performance of continuous composite girders (Kalibhat and Upadhyay 2020a). The assembled steel-prestressed concrete composite beam under the negative moment is studied (Wang et al. 2020m).

The dynamic characteristic of composite girders not only influences riding comfort, but also has closely relationship with safety. The numerical model that considers the slips and shear lag effects in the vehicle-steel-concrete composite bridge system is proposed (Zhu et al. 2020c). The modal parameters of steel-UHPC composite deck with large u-ribs are evaluated by the hammering experiment, and the differnece of the dynamic characteristics with the traditional orthotropic steel deck is compared (Zhang et al. 2020q). The spatial rigid model of composite beams is developed to determin the basic frequency, modals, the frequency response function and can estimate the stiffness of concrete and shear connectors (Abramowicz et al. 2020).

The degraded performance of composite beams is manifested in several aspects, such as stiffness degradation and load-bearing capacity reduction during the service stage. The adverse environment includes fatigue, corrosion, ultra-high and low temperature, freezing and thawing, sunlight and so on. Although researchers are paying much attention to the structure performance in their life cycles, due to the uncertainty of the component degradation and the difficulty of testing under multi-coupling effects, there are few related studies.

The redundant bearing capacity of double-steel box girder bridges with different damaged state under the concentrated load, including the light load, the heavy load, the cyclic load, is studied (Pham et al. 2021). Equilibrium equations are built to studied the long-term creep effects and simulate pouring in sections (Han et al. 2020a). The long-term stress distribution of push-out tests is studied by the ratio of creep methods in Ansys (Liu et al. 2019). Shadow recognition algorithm and simulation models are used to determine the temperature distribution of the composite bridges, in order to predict the effects of temperature on the bridge in the future (Zhang et al. 2020b). The fire resistance of prestressed composite beams and composite box girders is studied (Zhang et al. 2020d; Zhou et al. 2019a), and a structural fire damage index is proposed (Kang et al. 2020b). Four full-scale tests to evaluate the method of UHPC-strengthened steel plate girder are conducted, and the full-height repair, half-height repair and the location of the welding bolts are studied, which provides a quick way to repair the steel plate girder bridge (McMullen and Zaghi 2020).

As for composite girders, the main focus is on I-shaped steel-concrete composite beams, other structural forms such as composite box girder and truss composite beams are relatively less studied. Among them, there is more research on composite girders with corrugated steel webs, which is inseparable from domestic development. The combined effect of the composite beams and the stress distribution of each component under various stress states still need further attention.

5 Advances in bridge seismic resistance

5.1 Overview

Generally bridges are often located in the transportation throat and are key connection nodes in the lifeline system. Earthquakes may cause huge damage to the bridge structures, such as local damage and even collapse. Once the bridges collapsed, not only the traffic is blocked but also the earthquake relief activities are hampered. Therefore, how to reduce bridge damage and prevent bridge collapse is a key and hot issue in bridge engineering. Following the release of the "2019 Progress 15: Bridge Seismic Resistance" of the Bridge Department of Southwest Jiaotong University, the "2020 Bridge Seismic Advances" summarizes the researches of scholars from various countries in the field of bridge earthquake resistance.

5.2 Seismic performance of bridge piers

Bridge piers are buildings that support the upper structures of the bridges, and are the main lateral force resisting members under the action of earthquakes. Studies have shown that the damage of bridges under earthquakes is mainly the damage of substructures. Therefore, research on the seismic performance of bridge piers has always been a hot spot in related fields.

5.3 Seismic performance of traditional reinforced concrete bridge piers

The relevant investigations revealed that the damages of pier were significantly responsible for the failure of overall bridge structure system subjected to ground motion.

Zhang and Lu (2020) proposed a method to analyze the seismic reliability of bridge piers based on the first four-order moments of the structural response extreme value. This method provides an effective way to evaluate the seismic reliability of bridge piers. Li et al. (2020i) evaluated the seismic performance of typical reinforced concrete Y-shaped bridge piers (Fig. 13) under strong earthquakes on the basis of finite element simulation. Some scholars have studied the use of new concrete materials to replace ordinary concrete to improve the seismic performance of piers. For example, Tai et al. (2020) studied the use of lightweight aggregate concrete to replace ordinary concrete to reduce the structural weight and improve the deformation capacity of the pier column, thereby reducing the seismic response of the bridge under strong earthquakes.

5.3.1 Seismic performance of precast segmented bridge piers

For prefabricated bridge piers, the effective connection between segments and segments and between segments and foundation seriously affects the seismic resistance of the structure. Liu et al. (2020k) established three 1/4 scaled column models for a certain actual precast bridge project, conducted experimental research under cyclic loading, and studied the seismic performance of grouting sleeves connected to precast bridge piers. Wang et al. (2020n) proposed a new connection method of large-diameter steel bars overlapping ultra-high performance concrete grouting for prefabricated pier columns, and studied the effect of slippage on the seismic performance of pier columns (Fig. 14).

Some scholars discussed the seismic response and energy dissipation capacity of the precast segment assembled bridge piers. Wang (2020i) compared the seismic performance of prefabricated bridge piers with external energy-dissipating steel plates, integrally cast-in-place piers, and prefabricated bridge piers with built-in energy-dissipating steel bars.

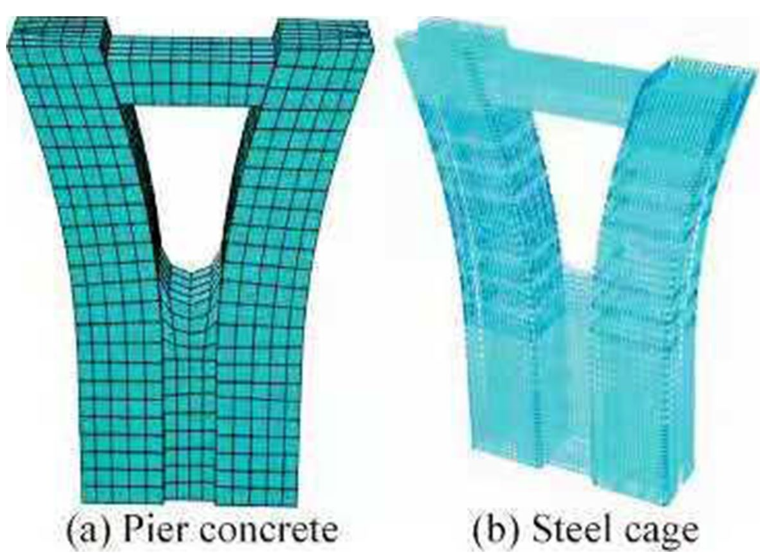

Fig. 13 finite element simulation model of Y-shaped pier (Li et al. 2020i)

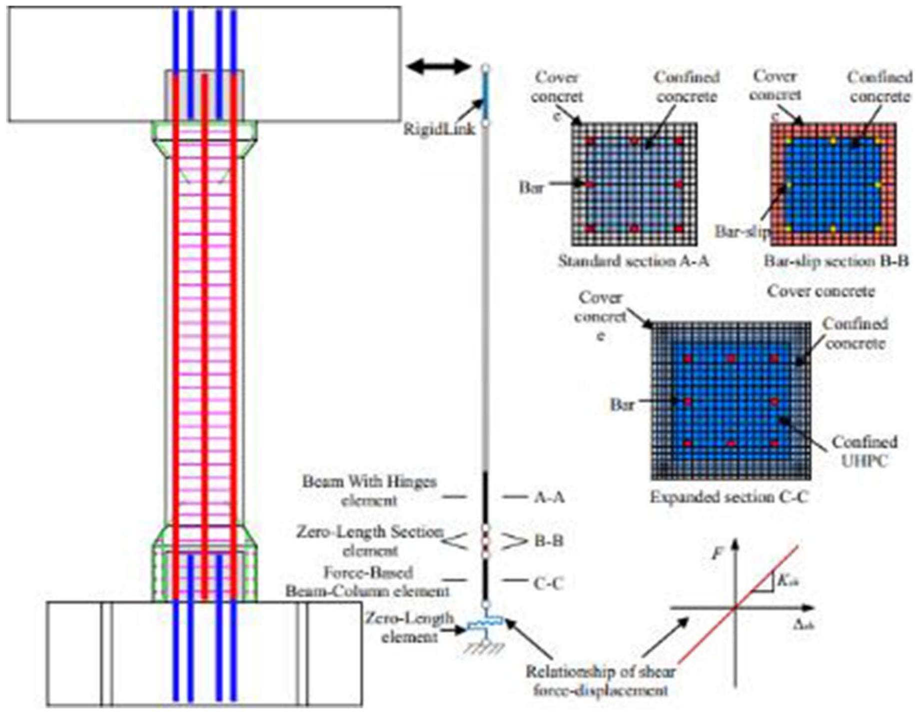

Fig. 14 Finite element model (Wang et al. 2020n)

5.3.2 Seismic performance of new structure piers

The seismic design of bridges gradually develops towards post-earthquake recoverability. Many new types of structural piers with post-earthquake recovery functions such as swing isolation piers, self-resetting piers and piers with replaceable components have emerged. Zhuo et al. (2020) and others creatively proposed the design concept of a box-shaped high-pier bridge with a combination of steel tube concrete columns and mild steel energy dissipation elements based on the principle of recoverable functional seismic design. Thomaidis et al. (2020) discussed the concept of bridge sway isolation considering the impact of abutment backfill system, and derived a new relationship for the prediction of bridge sway motion.

5.3.3 Seismic performance of reinforced bridge piers

Most of the existing reinforced concrete bridge piers were built before the 1980s. Under the modern anti-seismic design concept, their pier columns are generally weak in earthquake resistance. Pan et al. (2020a) and others studied the seismic performance of domestic nickel-titanium-niobium shape memory alloy (NiTiNb-SMA) wire actively restrained and strengthened reinforced concrete piers. Huang et al. (2020c) and others have conducted in-depth studies on the influence of the full-length reinforcement of the round steel pipe, the sleeve reinforcement and the local reinforcement of the pier bottom on the seismic performance of RC circular cross-section bridge piers.

5.3.4 Seismic performance of bridge tower

With the continuous increase of bridge spans, research on the seismic performance of long-span bridges such as suspension bridges and cable-stayed bridges has become one of the most concerned topics for scholars at home and abroad. Zheng et al. (2020a) studied the influence of the tower-beam connection method on the seismic response of a multi-tower suspension bridge. Zhang et al. (2020a) discussed the influence of different types of ground motion on the seismic response of various tower-type cable-stayed bridges based on the actual plan of a cable-stayed bridge.

5.4 Bridge seismic measures

The research on bridge seismic measures this year is mainly in three aspects: the types of bridge piers, the supporting structure and the new type of dampers.

5.4.1 The form of the pier type of piers

Scholars' research on the seismic performance of bridge piers this year is mainly to study the seismic performance of different types of bridge piers, mainly single- limb- to- double-limb thin-walled high piers, double-limb thin- walled piers, rectangular hollow double-column high piers with energy dissipating coupling beams.

Chen et al. (2020a) used low-cycle repeated load tests to explore the effects of different axial compression ratios, main reinforcement ratios and volumetric stirrup ratios on the seismic performance of double-limbed thin-walled piers of long-span continuous rigid frame bridges. The failure characteristics, hysteresis curve, displacement ductility and energy consumption performance of each test pier were obtained. It is concluded that the double-limbed thin-walled pier with higher main reinforcement ratio has a fuller hysteresis curve and good energy dissipation performance. Appropriately increasing the axial compression ratio can significantly improve the ductility performance of the pier. Chen and Li (2020e) proposed a numerical model for evaluating the seismic performance of isolated bridge piers based on the results of pseudo-static tests, which was verified by shaking table tests.

5.4.2 Bearing structure

The bearing is the key hub connecting the upper and lower structures of the bridge, and its key role is to transfer the deformation and load of the upper structure of the bridge to the lower structure.

Gao (2020) analyzed the damping performance of friction pendulum bearings for long-span cable-stayed bridges, and finally adopted the scheme of setting friction pendulum bearings on both side piers and auxiliary piers. Chen (2020) used high-pier bridges as the research object to study the mitigation effects of different seismic reinforcement measures such as lead rubber bearings and rocking foundations on the bridge seismic response (Fig. 15). Huang et al. (2020c) studied the reliability of replacing unbonded laminated rubber bearings (ULNR) in these bridges with a new type of unbonded steel mesh rubber bearings (USRB).

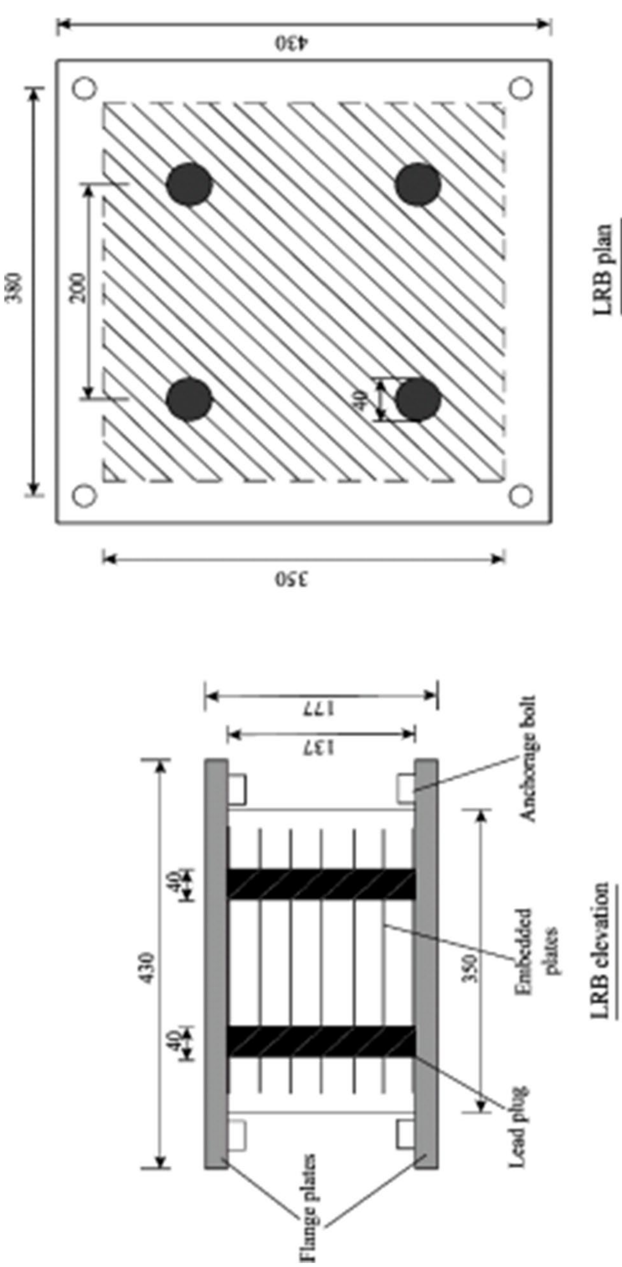

Fig. 15 Dimension drawing of LRB (Chen and Li 2020)

5.4.3 New type dampers

The damper is a kind of energy dissipation device in the bridge seismic design. The emergence of new materials and the continuous renewal and improvement of anti-seismic concepts, the types of dampers are gradually increasing, and the development of new dampers is also an effective aspect of improving bridge anti-seismic measures.

Niu et al. (2020) developed a new oil damper with variable stiffness, established its restoring force model and verified the working principle of the new oil damper through uniaxial dynamic tests, and compared the new oil damper with the existing two kinds of metals. The shock absorption performance of the damper, the new oil damper has a lower equivalent stiffness and higher energy consumption (Fig. 16). He et al. (2020a) studied the damping effect of mild steel dampers on a high-speed railway long-span deck concrete-filled steel tube rigid skeleton arch bridge, and found that the mild steel dampers had obvious damping effects on the arch bridge. The columns of the arch were installed with mild steel dampers. Its displacement damping rate reaches 43.5%, and the bending moment damping rate reaches 60.5%.

5.5 Contact problem

Contact research involves the superposition of multiple physical fields, mainly referring to the problems of soil-structure coupling, vehicle-bridge coupling, pier-water coupling, etc. under the action of earthquakes.

Recently scholars' research mainly focused on the seismic performance of bridges considering soil- structure interaction. He (2020b) used a performance-based comprehensive seismic evaluation method to evaluate the seismic performance of multi-span pile foundation bridges, explaining the impact of erosion depth and soil characteristics on the seismic performance of bridges. Liang et al. (2020b) conducted a centrifugal shaking table experiment on a pile foundation bridge (Fig. 17) to study the effects of seismic intensity, soil nonlinearity, soil-structure interaction and scour depth on the dynamic response of the bridge, and explained seismic performance of the lower bridge under the conditions of different scour depths.

In addition, some scholars have conducted research on vehicle-bridge coupling and pier-water coupling. Erdogan and Catbas (2020) conducted a numerical study on the

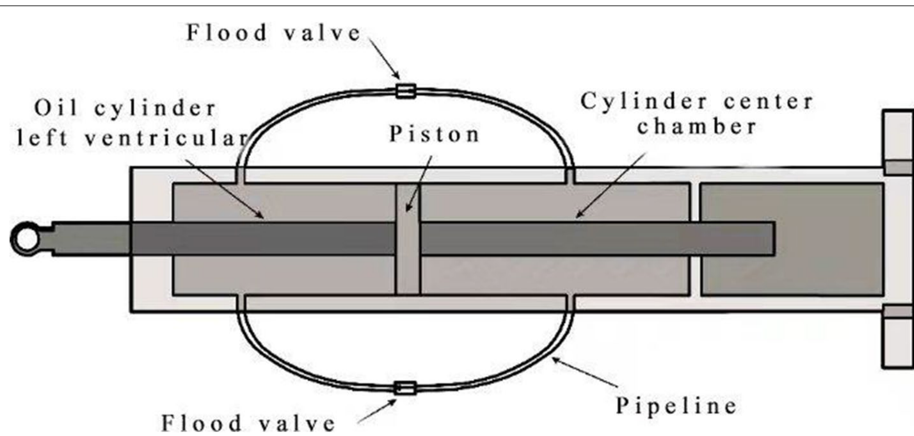

Fig. 16 Structural drawing of new type oil damper (Nin et al. 2020)

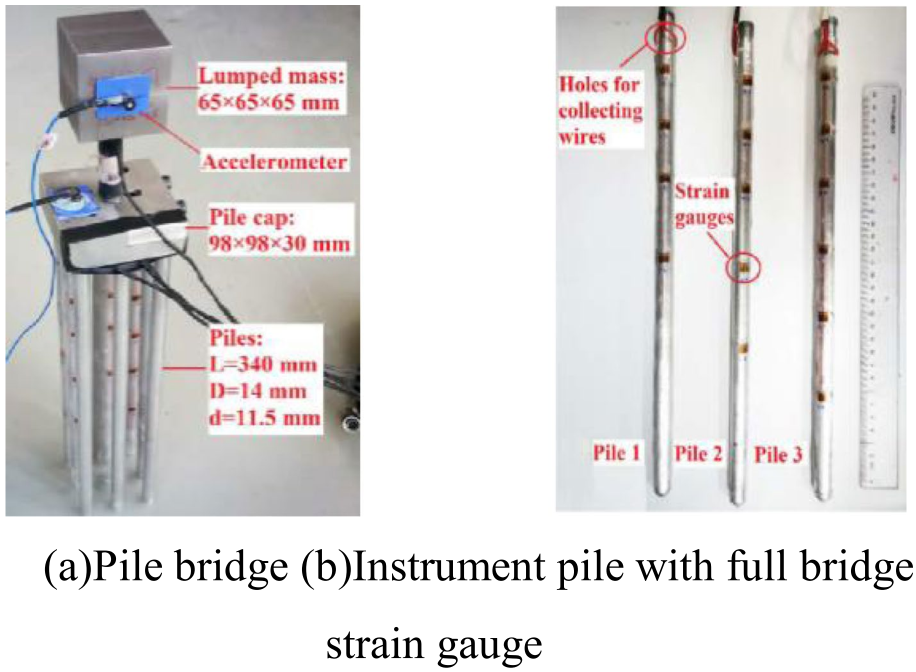

Fig. 17 Simplified bridge model configuration (Liang et al. 2020b). **a** Pile bridge **b** Instrument pile with full bridge strain gauge

dynamic response of a real highway bridge considering the vehicle-bridge interaction and strong earthquakes, and analyzed the effects of near-far-field seismic motion, vehicle speed, road unevenness, and soil-structure interaction on the seismic response of bridges.

5.6 Earthquake response

To ensure the safety and normal use of the bridge in earthquakes, and to prevent earthquakes and disasters in cities and regions, disaster reduction work and post-earthquake recovery and reconstruction work are of great significance.

5.6.1 Bridge seismic response

The study of bridge seismic response can comprehensively consider the impact of each key component of the bridge on the seismic performance of the bridge, which is mainly divided into the impact of component materials and combination types. The commonly used research methods are shaking table test and numerical simulation.

Scholars have conducted shaking table test studies on the seismic response of bridges. Lin et al. (2020) conducted a shaking table test on a concrete composite rigid frame bridge, and systematically studied its fault crossing angle and sinking steps. Duan (2020) used the principle of leverage to carry out a suspension bridge shaking table test (Fig. 18), and studied the influence of the corrugated steel girder beam on its seismic performance.

In addition, many scholars have conducted numerical simulation studies on the seismic performance and vulnerability of bridges. Xu et al. (2020c) revealed the impact of

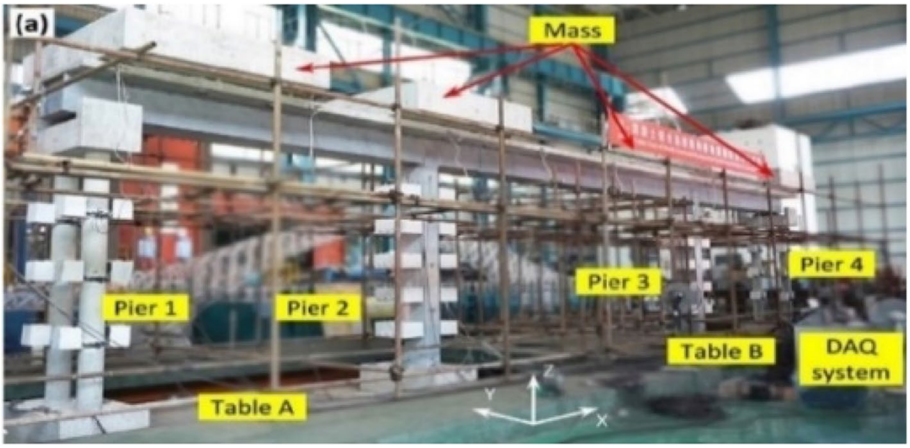

Fig. 18 Shaking table test of suspension bridge (Duan et al. 2020b)

service performance degradation on the seismic performance of prefabricated hollow slab bridges, and proposed a dynamic analysis method for the hinge degradation and material performance degradation of hollow slab bridges.

5.6.2 Bridge seismic system

Scholars have proposed optimizations to the existing bridge seismic system and expressed their views for future innovations in bridge seismic response. Huang et al. (2020f) proposed that the elastoplastic restraint device in the transverse direction could greatly reduce the seismic response of the structure. For the engineering application of the elastoplastic restraint device, the design idea of three seismic fortification lines was proposed to provide reference. Chen et al. (2020c) proposed a swaying double-layer bridge structure to make up for the lack of seismic damage control of double-layer bridges with traditional ductile seismic design.

6 Advances in bridge wind resistance

6.1 Flutter of long-span bridges

Sangalli and Braun (2020) conducted a numerical simulation of bridge flutter using sectional models with active control devices based on a fluid-structure interaction model and gave some preliminary results. Bera and Chandiramani (2020) proposed a method of bridge flutter control using rotating mass damper and winglets, which was verified to be effective for flutter suppression. Zhuo et al. (2021) studied and quantified the effect of active flaps on flutter of a streamline box girder. Sun et al. (2021) conducted the wind tunnel test of a suspension bridge with double deck and proposed some countermeasures for improving flutter performance. Mei et al. (2020a) studied the dynamic mechanism of enhancing flutter performance of streamline box girder by using an upper central board. Gao et al. (2020b) proposed an nonlinear aerodynamic model and conducted the prediction of nonlinear flutter of a bridge girder. Wu et al. (2020b) studied the effect of vertical motion on soft-flutter a truss girder. Wu et al. (2020a) reported a hysteresis effect of soft-flutter of a truss girder and explained the mechanism. Wang (2020l) proposed a amplitude-dependent aerodynamic model for the prediction of post-flutter and

VIV of a bridge deck. Some researchers conducted a novel prediction for bridge flutter using machine learning. Rizzo and Caracoglia (2020) and Abbas et al. (2020) proposed a method to calculated critical flutter speed using artificial neural networks respectively. Liao et al. (2021) conducted the flutter prediction of different streamline box girders using different method of machine learning and obtained satisfactory results.

6.2 VIV of long-span bridges

The VIV for the main girder of long-span bridges mainly affects the driving comfortability and structure safety, continuous vibration with large amplitude may result in fatigue failure of some key joint components. Consequently, VIV has been a key issue in the bridge wind engineering. The VIV event of the main girder happened on Humen Bridge in China in 2020 further promotes the research enthusiasm in VIV of long-span bridges. In this year, the researches mainly focus on two aspects, including (1) theoretical VIV models; (2) VIV performance evaluation and mitigation countermeasures for main girders and other bridge components.

In terms of theoretical research, many researchers established some theoretical models from the perspective of aerodynamic damping. Zhang et al. (2020e) compared the predictive capabilities and application scopes of five widely-used VIV models using the numerical examples involving a rigid rectangular 4:1 cylinder and two flexible cylinders. Gao et al. (2020a) pointed out that both torsional VIV and nonlinear flutter have the same nonlinear damping mechanism, the empirical self-excited force model for flutter analysis can be extended to interpret the torsional VIV. Wang et al. (2020l) proposed a nonlinear self-excited force model to describe the VIV and flutter for long-span bridges. Noguchi et al. (2020) raised a VIV amplitude evaluation method based on the flutter derivatives identified by the forced oscillation method with CFD simulation. Xu et al. (2020b) compared the predictive accuracy of the various single-degree-of-freedom VIV empirical models and found that the more accurate of the aerodynamic damping term was, the higher the predictive accuracy of vortex vibration was. In addition, Pagnini et al. (2020) proposed a simplified frequency domain analysis method to evaluate the "lock-in" region and amplitude of VIV based on Scruton number.

For the research of VIV performance and mitigation countermeasures, Pan et al. (2020b) studied the VIV performance and aerodynamic countermeasures for a multi box deck. Ma et al. (2020b) experimentally investigated the VIV performance of twin rectangular cylinders with an aspect ratio of 5:1. Wen et al. (2020a; b) investigated the effects of end conditions and aspect ratios on VIV for a rectangular sectional model and optimized the testing method for the aeroelastic model of continuous beams with multi-elastic support for higher-order modal VIV analysis. Cao et al. (2020) improved the dynamic monitoring system of a suspension bridge and proposed a hierarchical pre-warning system based on the comfortability of users. And also, the predictive accuracy of the VIV monitoring and the pre-warning system were verified by field measurement. Bai et al. (2021) systematically investigated the influence of the cross-sectional aspect ratio of composite beam with π shape on VIV performance and the mitigation efficiency of the different countermeasures was compared, including the fairing, inverted L-shaped edge plate, etc. Zhang et al. (2020p) studied the VIV performance of a two-box edge girder and proposed a measure of mini-triangular wind fairings to suppress VIV. Bai et al. (2021) improved the flutter and VIV stability of long-span bridges by sealing traffic barriers according to different rules. Zhan et al. (2020a) utilized wavy railings to generate three-dimensional disturbance flow to mitigate the VIV. The VIV suppressing mechanism of the spoilers on a streamlined closed-box girder were investigated by Hu et al. (2020a). The VIV mitigation efficiency of the self-issuing jet was further researched by Yang et al. (2020f) for a streamlined single-box girder at various angles of attack. The single-side pounding TMD (SS-PTMD) was employed to suppress VIV of long-span bridges by Wang et al. (2020j). Dai et al. (2020) suggested a method that used the equivalent damping ratio to characterize the contribution of TMD on the VIV mitigation, they found that the design formulas for the free-vibration suppression were the most robust option that avoids a high probability of failure. For the stay cables and other structures, Liu et al. (2020g) pointed out that the deformed cross-sections of real-world stay cables tended to be micro-elliptical and their aerodynamic performance was investigated using wind tunnel tests. Liu et al. (2020n) investigated the VIV of cables that happened on a long span cable-stayed bridge by field measurements. Chen et al. (2020d) studied the self-issuing jet method on suppressing the VIVs of a circular column by using digital pressure measurement. Chen et al. (2020) established an optimal design simulation model for suppressing the VIV of cylinders by introducing nonlinear energy sink (NES) vibration-absorber and based on the Van der Pol wake oscillator model and genetic algorithm. The aerodynamic characteristics and VIV performance of twin-box girder bridge were numerically investigated using the LES method with considering the three-dimensional feature of flow (Álvarez et al. 2021), and the wake flow around the girder was studied by DDES method to reveal the effect mechanism of the spacing between two boxes (Shang et al. 2020). Noguchi et al. (2020) numerically studied the flutter derivatives and aerodynamic damping by using forced oscillation method for a streamlined bridge girder, and the VIV amplitude was predicted by the method.

6.3 Buffeting of long-span bridges

The research progress on the buffeting of long-span bridges in 2020 mainly includes: (1) refined analysis of the buffeting response of bridge girders; (2) prediction of buffeting response of bridges in extreme and peculiar wind fields.

Regarding the refined analysis of buffeting response, Jian et al. (2020) studied the buffeting response of the main girder of a long-span cable-stayed bridge during the construction period under the conditions of oblique wind and tower interference through wind tunnel tests. Lystad et al. (2020) proposed a probabilistic model to consider the impact of turbulence uncertainty on bridge buffeting responses (see Fig. 19). Diana and Omarini (2020) studied the nonlinear effects of aerodynamic forces on the bridge girder through time-domain buffeting analysis. Solari and Martín (2021a, b) gave the general form closed solution of aerodynamic admittance of slender structures under arbitrary vibration modes based on the eigen-orthogonal decomposition method. Liu et al. (2020h) took the Taihong Yangtze River Bridge as an example to study the stress and fatigue failure of the bridge girder caused by buffeting. Wang et al. (2020f) conducted wind tunnel tests to study the aerodynamic admittance and buffeting correlation of twin-box girder with different slot widths. Zhou et al. (2020d) investigated the correlation of buffeting forces of typical bridge sections in different grid-generated turbulent

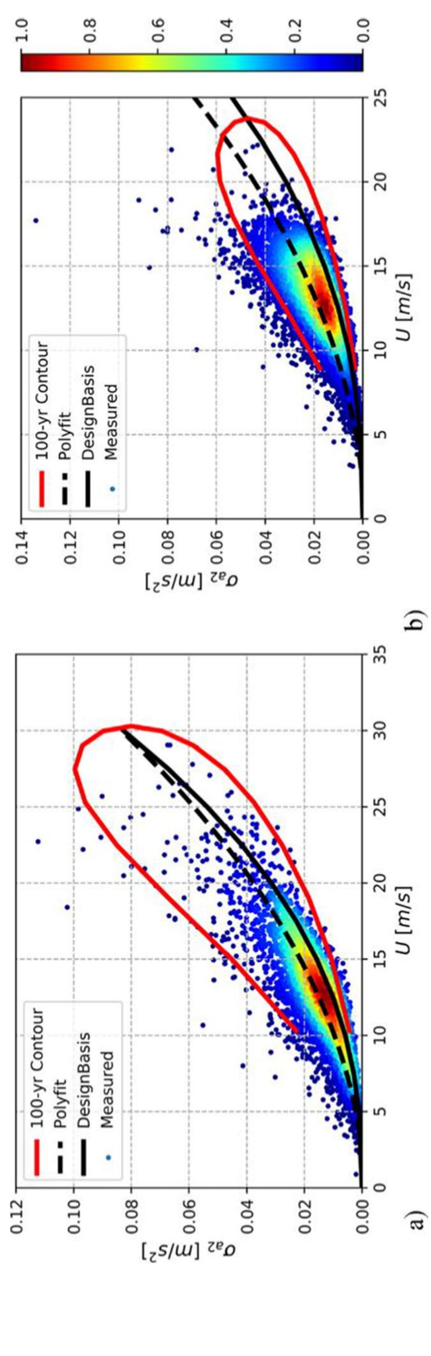

Fig. 19 Calculated and measured RMS girder acceleration response at the midspan: **a** westerly winds lateral response; **b** Easterly winds lateral response (Lystad et al. 2020)

flow fields. Shen et al. (2020b) studied the characteristics of the buffeting response of a double main girder sections with different slot width ratios under the condition that the aerodynamic force changes in the spanwise direction. Lei et al. (2020b) studied the buffeting performance of a cable-stayed bridge with a wide composite girder through wind tunnel tests. Xiang et al. (2020b) studied the buffeting forces of typical bluff body sections and their spanwise correlations in the flow fields generated by the active grids.

Regarding the prediction of bridge buffeting response under extreme and peculiar wind fields, Tao et al. (2020) conducted an in-depth analysis of bridge buffeting response with time-varying typhoon spectrum and coherence as input conditions. Shen et al. (2020d) studied the buffeting response of bridges located in a trumpet-shaped mountain pass under different incoming wind conditions. Wu et al. (2020c) proposed a buffeting time-domain analysis method that is suitable for long-span bridges in mountainous cities. Yan et al. (2020c) studied the buffeting response of the main girder of the long-span bridge during the construction period under the action of typhoon through field measurements. In addition to the above two aspects, some scholars have made new progress in buffeting design and vibration control of bridges. Cid Montoya et al. (2020) proposed a numerical analysis method that takes into account both the structural and aerodynamic characteristics of bridge girder (see Fig. 20). Phan (2020) studied the control effect of aerodynamic wings on the buffeting and flutter of the bridge through numerical analysis and wind tunnel tests. Yan et al. (2020b) controlled the vertical and torsional buffeting responses of the cable-stayed bridge during the construction period by installing diagonal wind-resistant cables, and achieved good vibration suppression effects.

7 Advances in train-bridge coupling vibration research

In current, the construction of railway bridges in China is facing new challenges induced by the larger bridge span, the higher operation speeds, and higher required comfort levels. Under the action of external excitations such as wind loads and train loads, the train-bridge interaction tends to be more significant. In 2020, researches about the train-bridge coupled vibration mostly focus on wind-train-bridge coupled vibration, including the wind field simulation of train-bridge system, aerodynamic coupling mechanism, refined analysis model and windproof measures. A brief review will be made on each aspect as follows.

7.1 Wind field simulation of train-bridge system

Based on the measured wind field, Li et al. (2021d) discussed the possibility of determining the composite wind speed standard through various methods depending on a typical mountainous bridge site; Liu et al. (2020q) monitored the wind field characteristics of Jingyue Yangtze River Bridge site, and found that the non-stationary characteristics of the average wind speed at the bridge site are significant; Zhou et al. (2018) found that the general wind at the bridge site exhibits relatively stable annual repeatability based on 6 years of wind data, and there are differences between the measured wind field parameters and the wind field parameters suggested by design specifications.

Based on the wind tunnel test, Song et al. (2020) studied the wind characteristics of the Y-shaped valley mountainous area of the proposed long-span bridge site, and analyzed the influence of the inflow field from the results of different test directions. In terms of

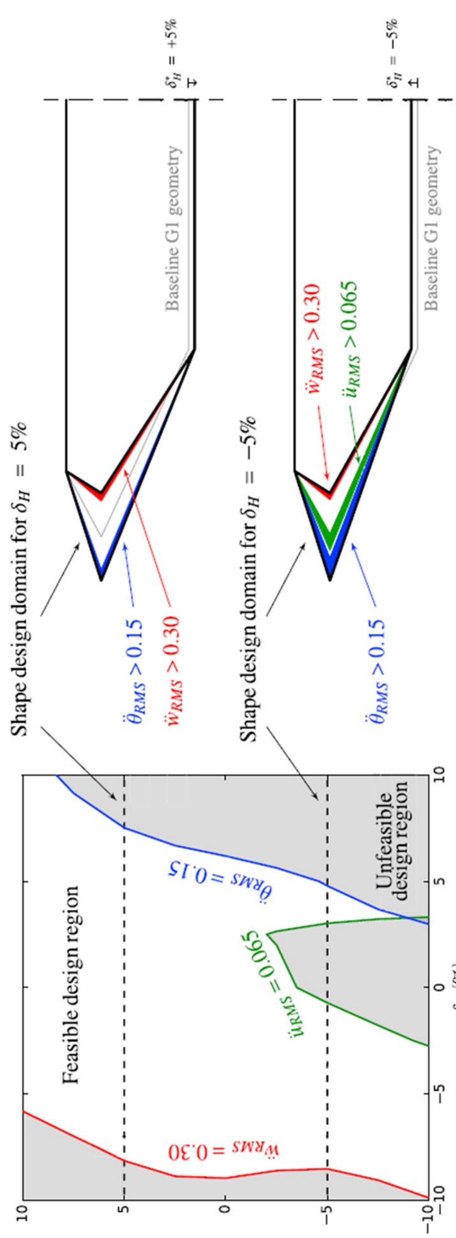

Fig. 20 Feasible design domain defined from the set of maximum root mean square of accelerations considered (Cid Montoya et al. 2020)

train wind field simulation, Su et al. (2020) tested the characteristics of the train wind field based on a moving train drive system, and compared the experimental results with the results of the Balzer and Cooper models, as shown in Fig. 21.

Based on numerical simulation, Shen et al. (2020a) conducted a refined analysis of the wind field at the canyon bridge site based on the WRF and CFD coupling models, and found that inlet boundary conditions with the considering the wind turbulence were in good agreement with measured values; Xu et al. (2019) used Evolutionary Power Spectral Density (EPSD) to characterize non-stationary features and improved the numerical simulation of turbulent wind field in long-span bridges.

7.2 Aerodynamic coupling mechanism of train-bridge system

The input wind load is a key to carry out the analysis of wind-vehicle-bridge coupling system, thus it will significantly impact on the dynamic response of train on the bridge. Zou et al. (2020a) developed a moving train-bridge wind tunnel test rig to study the aerodynamic characteristics of moving train, as shown in Fig. 22; Wang (2020h) adopted CFD dynamic grid to simulate and analyze the influence of different infrastructure on the aerodynamic characteristics of moving train; Based on wind tunnel tests, Zhou et al. (2020f) optimized the transverse arrangement of train by studying its influence on the aerodynamic characteristics of the train-bridge system.

At the same time, bridge towers, wind barriers, and two-car intersections can cause sudden changes in the aerodynamic characteristics of the train, which will affect the comfort and safety of the operating train. Yang et al. (2020c) studied the wind environment of the ring-shaped bridge tower area through numerical simulation, and found that there was a significant wind speed increase area around the bridge tower; Li et al. (2021c) studied the changes of aerodynamic characteristics during the trains crossing by using the wind tunnel test with a train moving on the simply supported beam. The research shows that the aerodynamic forces of trains on the leeward side will suddenly change during the crossing as shown in Fig. 23.

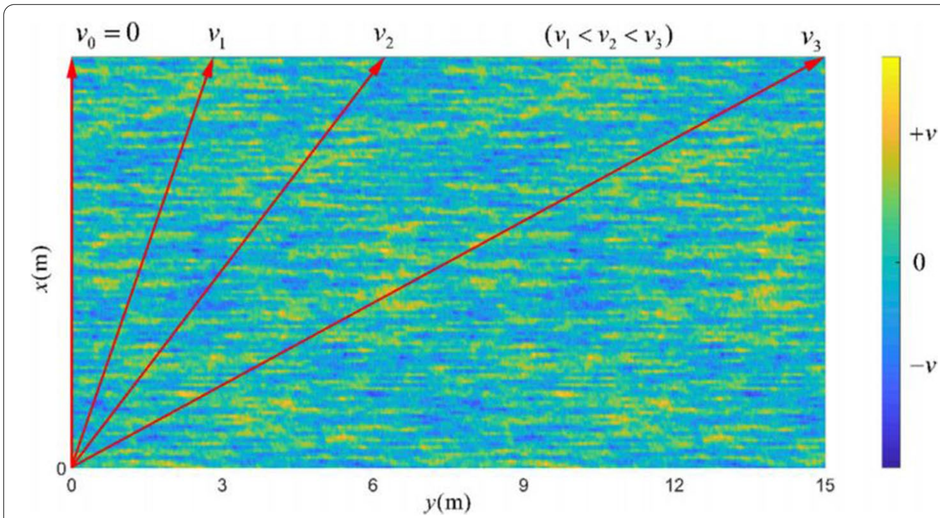

Fig. 21 The time and space path at the point of motion of turbulence (Su et al. 2020)

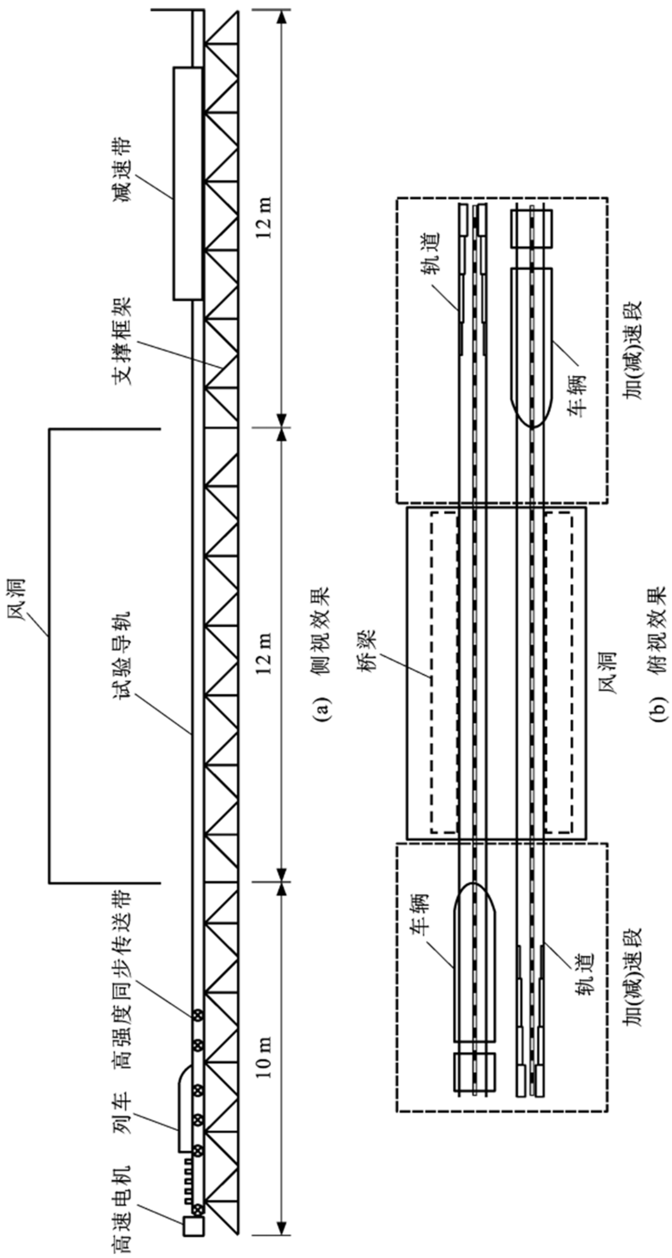

Fig. 22 Mobile train test plan (Zou et al. 2020a)

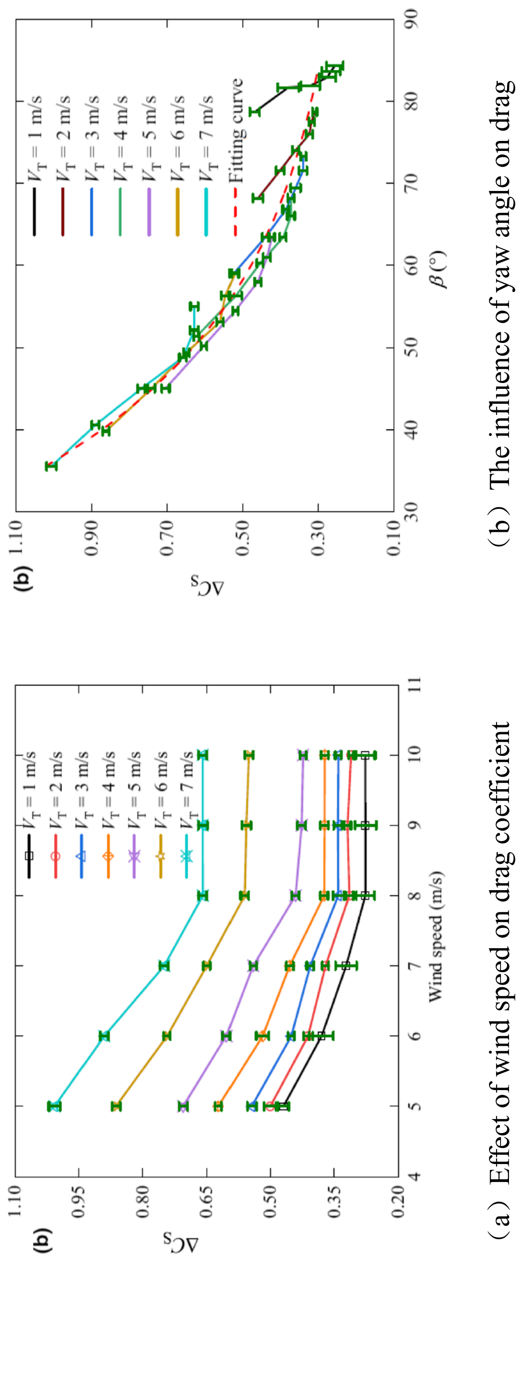

Fig. 23 Simple beam-moving train wind tunnel test (Li et al. 2021c). **a** Effect of wind speed on drag coefficient. **b** The influence of yaw angle on drag coefficient

7.3 Refined analysis model

Domestic and foreign scholars have established corresponding analysis models for different problems related to the safety and comfort of trains. By comparing the influence of track irregularities and bridge vibrations, Wang (2020h) found that the crosswind was the main cause to induce the train overturning, and bridge deformation can be approximately expressed as static deformation under the weight of the train. Then a simplified analysis framework for the overturning assessment of moving trains on bridges under crosswinds is proposed. Montenegro et al. (2020) analyzed the safety of the train under the influence of the CEN discrete gust model and random pulsating wind model, and then proposed a discrete gust model with temporal and spatial correlation characteristics according to the simulation results. In terms of co-simulation, the representative progress is mainly the research work carried out by Han et al. (2020b) and Cui et al. (2020b).

7.4 Windproof measures

The arrangement of wind barriers can effectively ensure the train's operating safety and comfort in the complex wind environment. The research of wind barrier mainly focuses on the influence of wind barrier on the aerodynamic characteristics and dynamic response of train. Zhang et al. (2020h) carried out a large-scale wind tunnel test to consider the influence of typical characteristics of wind barriers on the local wind characteristics of double-box girder bridge decks, as shown in Fig. 24; Gu et al. (2020b) used wind tunnel tests and numerical simulation methods to study the wind resistance performance and flow field characteristics of different bendable wave wind barriers on high-speed railways.

For the evaluation of the dynamic response of the train passing through above sudden wind field, Xu (2020d) studied the influence of the wind barrier permeability on the dynamic response of the train on the bridge based on a wind-train-bridge coupling system; Shi et al. (2020a) established a CFD numerical model and a wind-train-bridge coupling system to study the aerodynamic characteristics and driving safety indicators of the high-speed train on the tunnel-bridge-tunnel line under the crosswind environment, as shown in Fig. 25.

8 Advances in bridge hydrodynamics

Sea-crossing bridges face complex hydrodynamic loads, such as wave, current, wind-wave joint loads, etc. Meanwhile, fluid-structure interaction, local scour, and multiple hazards also affect the structural dynamic response significantly. To better understand the state-of-the-art of this field, this chapter reviews the journal articles published in 2020 with the following keywords "wave and current load", "local scour", "fluid-structure interaction", and "multiple hazards", respectively.

8.1 Wave and current load

The bridges located in the marine sites suffer from a marine environment with big waves and rapid currents. Wave and current loads make the bridge different from those on land. The research related to the wave and current load on the sea-crossing

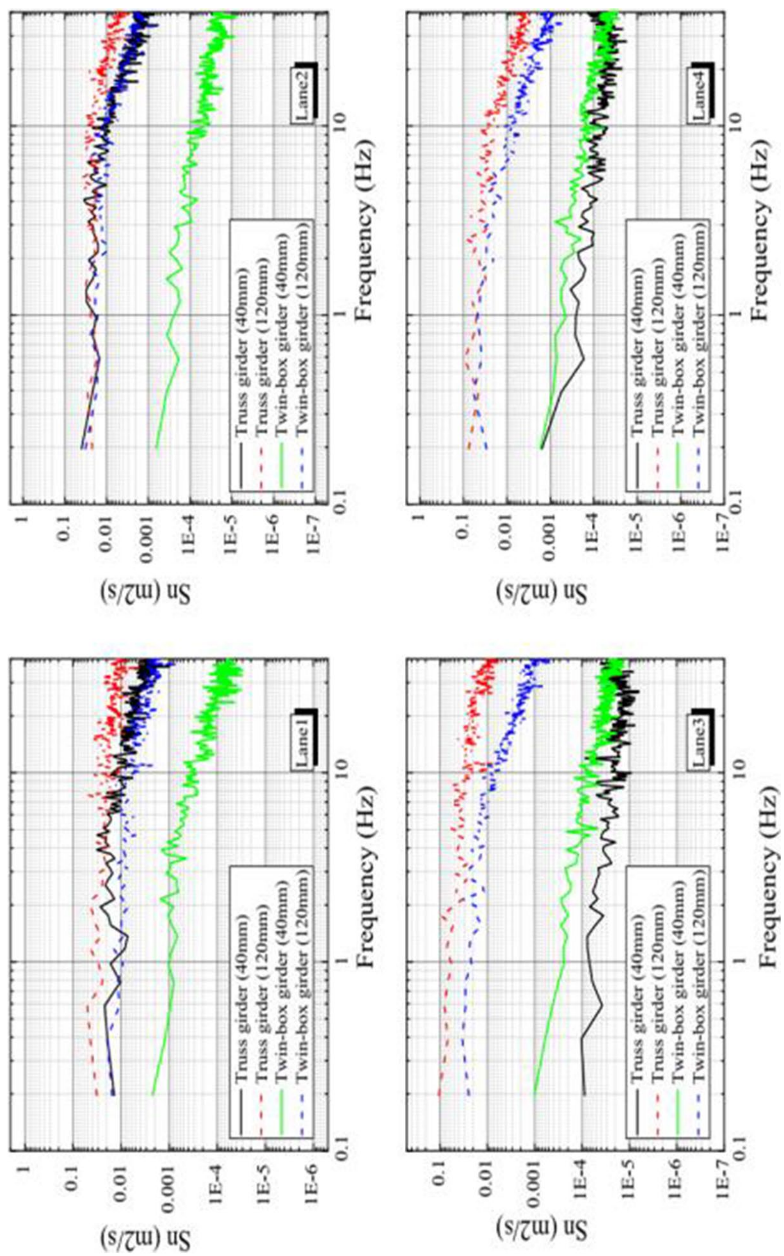

Fig. 24 Power spectrum characteristics (Zhang et al. 2020d)

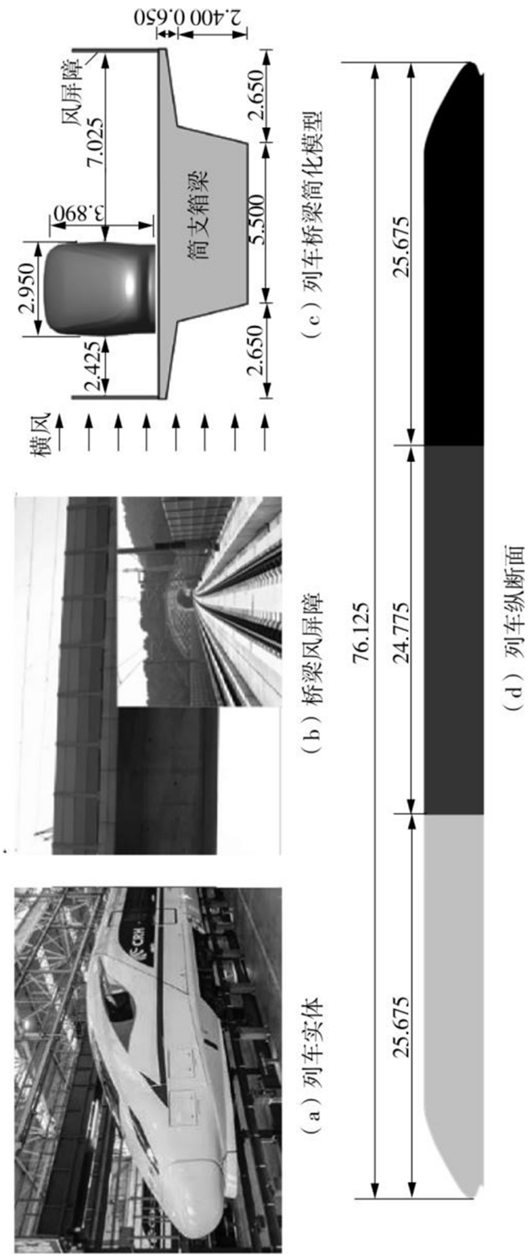

Fig. 25 Geometric model (unit: m) (Shi et al. 2020a)

bridge mainly focuses on the extreme wave load, current load, and wave-current interaction.

The load due to normal waves has been widely investigated in previous studies. The effect of extreme waves on sea-crossing bridges is the hot spot of the current research in 2020. Huang et al. (2020) developed the analytical calculation method of wave loads on the box-girder superstructure of coastal bridges in the submerged condition based on potential flow theory. Matemu et al. (2020) established a one-way coupled diffraction/trapped air model for predicting wave loading on bridges. At present, the definition of an extreme wave is not clear, and the wave conditions used in the other studies are pretty different. Zhu and Dong (2020) studied the effects of many parameters, including water depths, submergence depths, and wave heights, on wave-induced force on the bridge superstructure. Shen et al. (2020c) studied the effect of the length-width ratio of the round-ended piers on wave run-up, wave-particle velocity, and wave loads on the pier. Xu et al. (2020) used Stokes fifth order wave to simulate extreme wave, studied the influence of wave height, cap clearance height, and pile group on the impact load, and found that wave height and cap clearance height affected the wave loads significantly. Wei et al. (2020c) investigated the temporal and random characteristics of wave impact load and found the marginal distribution and their joint distribution form of impact maxima and the rising time of the wave impact load. Ti et al. (2020) analyzed the typhoon wave spectrum at an actual bridge site during typhoon Dujuan in 2015. They assessed the stochastic structural responses of an example sea-crossing cable-stayed bridge under random waves by employing measured and empirical wave spectra. They finally developed a frequency-domain approach as an efficient alternative for structural response analysis.

The current force and flow field on the bridge depends on the cross-section of a structure. Yang et al. (2020e) analyzed the influences of the free surface and the bottom condition on vortex structure. They found that each section's resistance and lift characteristics varied with the water depth. Wei et al. (2020b) studied the features of the flow field and turbulence around and inside the caisson at different flow velocities and water depths. They concluded the current force on the caisson as a function of the caisson bottom location.

Kang et al. (2020) studied the interaction between rectangular cofferdams with different length-width ratios (1.0, 1.5, 2.0) and oblique wave-current interaction with a rectangular bridge cofferdam under different length-width ratios, and found that the influence of wave-current incident angle on the total wave current force increased with the increase of aspect ratio and influence coefficients of incident angles on wave-current forces or wave forces were relatively close.

8.2 Local scour of bridge foundation

The local scour process includes the interaction of flow, sediment, and structure, involving hydrodynamic and sediment transport theory. Thus, the scour mechanism is very complex. Most of the relevant papers in 2020 focused on the scour depth prediction, scour monitoring, and local scour countermeasures of bridge.

The predictions of local scour include more influencing factors, including the structure shape, flow factors, and sediment conditions. Abbas et al. (2020a, b) studied the influence of the inclination angle of the double-column pier on local scour and found that the scour depth decreased with the increase of the included angle. Solati et al. (2020) explored the influence of time-varying flow and the duration of flow reaching the peak on local scour. Xiang et al. (2020) compared the local scour under unidirectional and tidal currents and concluded that the scour development rate and maximum scour depth under tidal current were lower than that under unidirectional currents. Clarifying the influence degree of each factor is necessary and deserves further study to predict the scour depth accurately.

The monitoring of local scour mainly focuses on the monitoring methods and equipment. Maroni et al. (2020) introduced a scour monitoring system that applied electromagnetic sensors to monitor extreme flood conditions. Wan Mohtar et al. (2020) studied the imaging technology for scour monitoring and realized continuous monitoring of local scour.

The protection of local scour mainly focuses on the study of protection and arrangement forms. Ferraro et al. (2020) found that the standard collar and the hook could significantly reduce local scour depth and scour volume. Pandey et al. (2020) studied the protective effect of the height and diameter of the collar on local scour, and put forward the formula for calculating the scour depth of the piers with collar. Nazari-Sharabian et al. (2020) studied the protective effect of the number and location of sacrifice piles on local scour and proposed the optimal arrangement of scour prevention for different pile numbers.

8.3 Study of fluid-structure interaction for deep-water bridges

The fluid-structure interaction affects the vibration of the submerged pier and foundation and hence affects structural dynamic response. The papers published in 2020 mainly focused on the seismic analysis of deep-water bridge considering fluid-structure interaction. Greco et al. (2020) simulated the coupling effects between the fluid and the structure using a moving mesh method based on an arbitrary Lagrangian–Eulerian approach to take bridge deformability and moving wall conditions into consideration. Ma et al. (2020a) constructed a 2-degree-of-freedom bridge analysis model considering the fluid-structure interaction, and set up a nonlinear viscous damper in the model, and found through the analyses that the viscous drag reduced the seismic response of the sea-crossing bridge effectively regardless of the fluid-structure interaction. Zhang et al. (2020) put forward the formula of hydrodynamic added mass of rectangular cap by Bayesian updating approach and verified the formula's accuracy through the fluid-structure interaction numerical model and flume experiment.

8.4 Multi-hazard effect of the extreme marine environment on the sea-crossing bridge

The sea-crossing bridges are vulnerable to multiple hazards, for example, wind, wave, tsunami, earthquake, storm surge, etc. Many researchers were working on the risk of structural damage of bridges under multiple hazards in 2020. The destructiveness, group-occurring, and unpredictability of multi-hazard were considered to assess the bridge's safety in 2020. Snaiki et al. (2020) proposed an effective methodology to determine the hurricane wind and storm surge hazards to coastal bridges under changing climate conditions. Fiorillo and Nassif (2020) used probabilistic risk methodologies and data from the National Bridge Inventory database to identify, assess, and quantify structural risk components to bridges. Balomenos et al. (2020) developed fragility models for individual spans of different bridge classes (concrete girder, steel girder, slab, box girder) considering spatial variability of wave loads and variations in structural characteristics.

9 Advances in durability of concrete bridges

The durability of the concrete bridges directly affects the safety of the bridge and the service life of the concrete bridges. The actual use environment of the bridge is complex, the external environment of the bridge and loads applied on the concrete bridge affect the durability of the bridge significantly. For the concrete bridge, due to differences in the location, actual use environment, and force conditions of the different bridge components, various durability problems can occur during their service life.

9.1 Major durability problems of the materials in concrete bridge

9.1.1 Alkali-silica reaction (ASR)

The alkali-silica reaction has a negative impact on the concrete members in various parts of the bridge, which leads to the durability problems of the concrete bridge. The establishment of the ASR model can effectively provide the behavior characteristics of concrete components under ASR failure conditions. Allahyari et al. (2020) established a robust time-dependent ASR model by combining chemo-mechanical and kinetics-based approaches to analyze the expansion of ASR in concrete structures. Compared with the previous similar alkali-silica reaction expansion model, the proposed new model has higher accuracy in predicting the concrete structure behavior with alkali-silica reaction. Karthik et al. (2020) studied the effects of ASR and delayed ettringite formation on the large reinforced concrete beam-column joints by considering the concrete protective layer, the core concrete material properties, and the influence of the passive prestressing effects on the longitudinal and transverse reinforcement. The results showed that the mechanical properties and toughness of concrete components increased with the increase of the passive prestress generated by the formation of the alkali-silica reaction and the ettringite. However, the energy absorption properties of severely corroded components will be reduced by about 59%. Sanchez et al. (2020) applied surface observations and multi-level testing methods to evaluate the effects of ASR on a highway bridge structure after nearly 50 years of service. The condition of the overpass was assessed and the study found that compared with the upper part of the bridge deck, the bottom of the bridge deck was more severely damaged by the expansion of ASR due to factors such as high humidity environment, high corrosion of steel bars, loading, and restraint effects. The production of ASR may affect the aggregate interlock resulting in the reduction of the shear resistance of the components. To make full use of the existing inspection data to effectively analyze the ASR problem in bridge concrete members, Ogawa and Chikata (2020) used a statistical method called topic model to analyze the data and content in different bridge inspections reports. The topic model can statistically analyze the failure characteristics of bridges under different conditions to provide an effective guidance for bridge maintenance and management. The research focused on the analysis of bridge inspection reports related to ASR damage and high frequency of keywords such as "Crack", "ASR", "turtle-shaped". The damage characteristics of the bridge after the alkali-silica reaction occurred were summarized. Thus, the ASR damage in the bridge structure can be determined rapidly to facilitate repair and maintenance of the concrete bridge.

9.1.2 Sulfate attack

To study the influence of sulfate attack on concrete specimens of the bridge under bending fatigue load and wet-dry cycle conditions, Liu et al. (2020a) evaluated the coupling effect on the concrete integrity and mechanical properties by considering the change of mass loss rate and relative dynamic elastic modulus. The sulfate content inside the concrete was measured to assess the permeability of sulfate ions under different experimental environmental conditions. The results showed that the water convection and the diffusion phenomenon caused by capillary effects, the concentration gradient, bending fatigue load, and dry-wet cycle conditions can accelerate the migration of sulfate ions in concrete and the degree of concrete deterioration. Zhang et al. (2020) used microscopic scanning and mechanical performance testing methods to study the shear resistance of concrete members under sulfate attack conditions and found that the shear strength of concrete decreased with the increase of sulfate attack time. The failure mode of specimens under different sulfate exposure conditions varied due to the different erosion mechanisms. The main failure modes of fully-immersion of concrete specimens are aggregate rolling, peeling, and slippage of the cement matrix near the shear surface. However, under semi-immersion conditions, the concrete specimens are mainly damaged by physical crystallization, and the main damage modes are matrix cracking and dilatancy slip. To further study the influence mechanism of sulfate on the pore structure of concrete in different immersion environments, Zhang et al. (2020w) investigated the degradation characteristics of concrete under different sulfate erosion conditions from the level of microscopic pore structure. They proposed that reducing the initial content of large pores (1–100 μm in diameter) in concrete structures will potentially reduce the physical damage to concrete components caused by sulfate attack.

9.1.3 Freeze-thaw cycles

Saydan et al. (2020) established a finite element model based on the measured data of different types of aggregates used in the Misirlioglu Bridge and simulated the structural behavior of the bridge before and after the freeze-thaw cycle under the existing loading conditions. Under the loading condition, the stress of the bridge components was distributed on the surface of the overall structure. However, the structure could easily lose the bearing capacity after the freeze-thaw cycle and the stress was concentrated on the local components. Xu et al. (2020) evaluated the aging resistance of the new bridge deck paving material polyether polyurethane concrete and found that under different aging conditions, the splitting strength of polyether polyurethane concrete after freeze-thaw cycles was significantly higher. For unaged SBS modified asphalt, polyether polyurethane concrete has good aging resistance and durability and can be used as a long-term service bridge deck paving material. Moradllo et al. (2020) used the time to reach critical saturation (TTRCS) model to evaluate the durability of concrete components under freeze-thaw cycles. They studied 30 concrete components with different water-cement ratios, porosity, and pore distribution. When the water reducing agent and air-entraining agent were used at the same time, they could react with each other, increasing the pore spacing inside the concrete. This indicated that the amount of required air-entraining agents was increased when the superplasticizer was used. In concrete specimens with a low water-cement ratio, the pore diameter and the pore connectivity were reduced, therefore, time to reach the critical point of saturation was increased and the performance of the concrete against freezing and thawing cycles could be improved.

9.2 Corrosion of steel bars in the bridge structure

In addition to the damage of the concrete base structure and the concrete protective layer, the corrosion of the steel bars in the reinforced concrete is also an important reason for the deterioration of the durability of reinforced concrete bridges. During the service of reinforced concrete bridges, harmful substances in the environment (such as chloride ions and CO_2, etc.) gradually penetrate the concrete layer and migrate inside the concrete resulting in the destruction of the steel passivation layer and the corrosion of the steel.

The corrosion of steel bars caused by the carbonization of concrete is also one of the most common problems affecting the durability of bridge structures. To consider the impact of CO_2 changes in the atmosphere on the concrete structure, Ekolu (2020) studied the natural carbonation prediction model and discussed the development of carbonation in concrete as well as the service life of concrete structures based on the global CO_2 concentration change forecast data (by 2100) and considering environmental factors (including climatic conditions in inland and coastal subtropical regions). The results of the study showed that with the increase of CO_2 concentration, the carbonation depth of ordinary strength concrete would increase by 31% and the service life would be reduced by 24%. For the concrete structures, due to the increase in atmospheric CO_2 concentration, the corrosion rate of steel bars can be accelerated leading to increased bridge repair and maintenance costs. Given the increasing concentration of CO_2 in the atmosphere, it is necessary to pay more attention to the design of concrete strength grade and protective layer thickness in the design of concrete structures. The model for predicting the corrosion of steel reinforcement caused by the carbonation of concrete structures plays an important role in guiding the durability design of bridges, the maintenance as well as repair of old bridges, and the evaluation of bridge durability. Common natural carbonation models are mainly established based on experimental data such as accelerated carbonation tests. It is difficult to accurately predict the natural carbonation and corrosion process of actual concrete structures. To improve the accuracy of the existing reinforced concrete carbonation prediction model, Gu and Li (2020) proposed a method based on the Bayes theorem to modify the corrosion and cracking model of reinforced concrete structures caused by carbonation according to the measured data. The proposed method provides a powerful tool that enables the existing prediction models to assess the degradation degree of reinforced concrete components in the service environment and the durability of the structure more accurately. Jung et al. (2020) proposed a concrete deterioration prediction approach by combining Fick's first law and Bayes' theorem based on field measurement data of bridges in service for more than 19 years. The carbonation prediction approach took into account the design parameters including diffusion coefficient, CO_2 concentration, CO_2 absorption, and hydration degree. The principle of the concrete carbonation prediction method was verified by the field measurement data of bridges in different parts of South Korea. The new prediction approach can predict the carbonation process of reinforced concrete members under different environmental conditions well. The prediction results can effectively provide targeted maintenance programs for in-service concrete bridge structures. Sun et al. (2020a) studied the degradation process of concrete carbonization, steel corrosion, and accumulated cracks on the surface of the protective layer, and proposed a comprehensive probabilistic analysis approach in consideration of the uncertainty of the actual use environment, materials, and structural characteristics. This approach added the correction and error terms to the existing models. In addition, the parameters in the model are improved and calibrated using Bayesian theory based on field measured data, which can analyze the cracking of reinforced concrete caused by corrosion to achieve more accurate prediction results and meet structural durability design requirements. Pietro et al. (2020) proposed an effective evaluation approach for the collapse of in-service highway bridges under horizontal load. A simplified model was established by reducing the number of steel bars and applying multi-modal pushover analysis methods to consider the corrosion of steel bars caused by carbonation. This method can identify the concrete component that first reaches the collapse condition in the bridge structure and provide effective information for the maintenance, repair, and reinforcement of the bridge.

9.3 The influence of different environments on bridge durability

Different environments have obvious effects on the durability of bridges. For example, harmful ions contained in the marine environment and changes in temperature during climate change can potentially increase the rate of degradation of concrete bridge structures and reduce the durability of the concrete bridge. Therefore, understanding the degradation behavior of bridges in different actual use environments is of great significance to the design and evaluation of bridge durability.

9.3.1 Marine environment

Xie and Li (2020) investigated the impact of the coupling effects of ocean currents and waves on the durability of cross-sea bridge pier structures in the ocean environment and found that the damage of the bridge pier structure was related to the composition of the bridge pier material and the degradation of the whole structure performance under the action of a special environment. Zhou et al. (2020b) carried out a 4-year exposure experiment of concrete bridge structures in atmospheric and marine environments in Japan. They pointed out that the chloride deposition in the concrete structure was not only related to time but also closely related to the local climate and geographic conditions where the components were located. The chloride deposition on the bridge surface can be increased significantly during the typhoon and rain periods. The influence of chloride on the surface of the specimen is related to the distribution of rainwater and the average rainfall, which affects the scouring effect and permeability of the specimen. The research results help to determine the key points of bridge maintenance in a more detailed marine environment and to save the maintenance and repair costs by carrying out targeted maintenance of the bridge.

9.3.2 Climate change

Shirkhani et al. (2020) studied the impact of temperature rise on the design service life of concrete bridge decks under different climate change conditions in different regions of Canada. Ten global climate models under 3 representative concentration pathways were studied. The results indicated that by the end of the twenty-first century, the average design life of ordinary cement concrete and high-performance concrete bridge slabs would be reduced by 50% and 33%, respectively. Guest et al. (2020) explored the methodology of establishing a bridge deck design model by considering the deterioration of reinforced concrete during climate change. The established model simulated three deterioration stages of the concrete bridge deck including the generation of steel corrosion, the generation of concrete cracks, and the propagation of cracks. The study showed that the impact of climate change on the service life of bridge decks mainly depended on the durability design of the bridge deck.

9.4 Improvement of concrete bridge durability

The improvement of concrete bridge durability facilitates the cost reduction of the concrete bridge maintenance and the service life elongation of the bridge. Sheng et al. (2020) found that using kaolin as an additive to partially replace ordinary Portland cement in reinforced concrete structures could effectively reduce the corrosion of harmful ions on the surface of steel bars. Chen et al. (2020b) found that the addition of steel fiber could increase the tortuosity of the internal cracks of the concrete and reduce the damage between the concrete and the steel under the load.

10 Advances in fatigue of steel bridge

Many efforts have been done on the research of fatigue of steel bridge in 2020. In the aspect of damage mechanism or fatigue assessment method, Yao et al. (2021) conducted stress monitoring for the cutouts in the diaphragms caused by manufacturing errors, showing that the manufacturing errors at the cutouts would lead to the transfer of the stress concentration area on the side with a smaller hole radius from the cutouts to the weld end of the longitudinal rib and diaphragms. Huang et al. (2020g) showed that stress concentration effect was caused by assembly tolerance resulting in a significant increase in stress amplitude on the welded toe of the butt weld, and a significant decrease in the fatigue performance. He et al. (2020) simulated the welding process of the rib-to-deck welded joints, and the analysis results showed that high welding residual stress occurred at the weld. Gadallah et al. (2020) studied on measuring residual stress distribution at the weld root of rib-to-deck joints using the contour method. Zhang et al. (2021) used the ultrasonic nondestructive testing method to study the welding residual stress distribution of an innovative double-side welded rib-to-deck joint, and the effects of geometric configuration parameters and welding parameters on welding residual stress had been analyzed. The results showed that ultrasonic nondestructive testing method is suitable for testing welding residual stress, and weld penetration rate, deck thickness, assembly gap and welding speed are key influencing factors of welding residual stress.

Li et al. (2020) proposed a fatigue performance evaluation method for steel bridges considering the train dynamic effect based on a vehicle-bridge analysis model composed of a 3D vehicle model, multi-scale bridge finite element model including the track system, and a wheel-rail interaction model. Ma et al. (2020) considered the effect of bridge foundation scour on the superstructure, carried out fatigue damage assessment on the welded joints of OSBs, and studied the reliability assessment of the structure according to the fatigue cumulative damage theory. Mashayekhi and Santini-Bell (2020) proposed a fatigue assessment protocol for these complex critical components of steel bridges, using the hotspot stress method and multi-scale finite element model. Yang et al. (2020b) investigated multiaxial fatigue property of key welding details in OSB crossbeam based on the structural stress method, and compared the evaluation results with the evaluation methods recommended by international codes and standards, such as the nominal stress method, hot spot stress method and notch stress method. On this basis, the effects of load modes and characteristic parameters on fatigue performance and failure modes of steel bridge deck are further studied. Zhu et al. (2020) monitored the wheel load stress response at the details with different cutout geometries of the steel bridge deck, and estimated the fatigue life of related structural details according to the AASHTO LRFD specifications. Ji and Chen (2020) verified the applicability of different extrapolation formulas suggested by IIW in hot spot stress analysis, and obtained relatively reliable fatigue performance evaluation results in combination with S-N curve provided by IIW. Yokozeki et al. (2021) made a comparative study on fatigue resistance of U rib, V rib and plate rib with diaphragm cross structural details respectively, and determined the reference points of hot spot stress extraction for cross details of different stiffeners. Liao et al. (2020) carried out high cycle constant amplitude fatigue test and numerical simulation of fatigue crack growth for typical steel bridge cruciform fillet-welded joints, and the results showed that relatively accurate fatigue life evaluation results could be obtained by replacing initial defects with semi-elliptical cracks. Zhang et al. (2020a, b) investigated into fatigue resistance evaluation of the rib-to-deck welded joints based on equivalent structural stress method and strain energy density theory (2020). The results showed that the equivalent structural stress method was suitable for fatigue resistance evaluation of multiple fatigue modes of the rib-to-deck welded joints. On the other hand, fracture mechanics is mainly used to solve the fatigue problems of structures with crack defects, and the study of fatigue crack growth law of steel bridge deck based on fracture mechanics is the most direct and effective means to evaluate the fatigue fragility details. Cui et al. (2021) proposed a multiscale fatigue damage evolution model to assess the fatigue life of steel bridge.

In the aspect of anti-fatigue design methods, Jiang et al. (2020) compared and analyzed the local stress characteristics and equivalent stress amplitude of the traditional U-rib to deck structure detail, the new upsetting treatment of U-rib to deck structure and the new double-side U-rib to deck welding structure. The results showed that the upsetting treatment of U-rib could improve the fatigue resistance of U-rib weld toe and double-side welding could significantly improve the fatigue performance of weld toe and root. Fang et al. (2020) discussed the FEM method which was applicable to notch stress of double-side U-rib to deck welding structure, analyzed the influence of roof thickness and weld size on fatigue resistance and optimized the details of the structure. Pu et al. (2020) designed a full-length segment model with two U-ribs and two V-ribs and carried out fatigue test and research with the steel deck of long-span railway bridge as the research object. Zhang et al. (2020a, b) made a systematic theoretical analysis and experimental studies on the fatigue performance of rib-to-deck and rib-to-diaphragm joints, and compared various long-life structural details with the fatigue performance of steel bridge deck structure. The results showed the dominated fatigue cracking pattern of rib-to-deck joints changed into deck weld toe cracking of innovative double-side welding details from weld root cracking of traditional single-side welding details after introducing innovative double-side rib-to-deck welding joint, and the cumulative fatigue damage of structural details was greatly reduced and the fatigue life was significantly improved.

In the aspect of monitoring and detection of fatigue damage in steel bridge, Chen et al. (2020) used ultrasonic testing method to realize the accurate identification of internal defects of U-rib full penetration fillet weld of steel bridge decks. Sun et al. (2020) proposed an ultrasonic double probe penetration testing method for longitudinal cracks at the rib-to-deck weld joint, and used prefabricated crack specimens to test and verify this detection method. Li et al. (2020) embedded piezoelectric ceramics in the steel-UHPC composite structure and applied excitation to generate ultrasonic wave, and to identify the local damage of the composite structure through ultrasonic signal. Duan et al. (2020) monitored the crack propagation process of steel bridge using acoustic emission sensor, and the results showed that this technology could capture dynamic fatigue crack information. Wang et al. (2020) extracted damaged dispersed signals in guided waves based on the singular value decomposition-based guided wave array signal processing approach. The actual analysis of steel bridge deck showed that the proposed method could successfully extract crack information from the measured signals with low signal-to-noise ratios. Solovyov et al. (2021) studied the blocking effect of steel bridge fatigue cracks on external heat transfer under natural environmental conditions, and the results showed that the passive infrared thermography could detect concealed fatigue cracks in steel bridge.

In the aspect of fatigue reinforcement and maintenance of steel bridges, Liu et al. (2020) studied the characteristics of crack opening closure morphology and closure depth under the combination of multiple impact factors, and the results showed that crack closure could be achieved by impacting at three times. Kinoshita et al. (2020) applied shot peening technology to the reinforcement of welding details of an existing steel bridge, and the results showed that this technology could introduce residual compressive stress at the welding toe and improve its fatigue strength. Chataigner et al. (2020) strengthened the butt weld of an existing bridge by bonding CFRP plates with epoxy asphalt adhesive. The vehicle loading test results showed that CFRP plates had good force transmission effect and could significantly reduce the stress amplitude at the weld. Jie (2021) pasted CFRP on the surface of the cross welded joint containing initial cracks to enhance its fatigue life. Mohabeddine et al. (2021) summarized the analytical model to predict the central crack growth law after CFPR bonding on both sides of the plane plate from the test data of multiple CFRP reinforced cracks. Mohajer et al. (2020) took steel plates with prefabricated defects as the research object and analyzed the reduction effect of bond slip on strengthening effect. Doroudi et al. (2020) conducted fatigue test and theoretical analysis on the bond slip relationship of CFRP-steel interface under cyclic loading, and established a plastic damage model to describe the bond slip relationship of the interface. Kasper et al. (2021) determined the creep characteristics of toughened epoxy-adhesives at different environmental temperatures and the S-N curve of toughened epoxy-adhesives joints by a series of tests. Tong et al. (2020b) designed the equal-amplitude tensile fatigue test of butt-welded thin-walled steel plates strengthened using CFRP sheets, and the results could provide a basis for the fatigue design of CFRP reinforced butt-welded structures. Wang et al. (2021; 2020) proposed a UHPC bridge deck reinforcement method by adding one-story transverse steel bars on the top of orthotropic steel deck in Junshan Bridge. The comparison of test results showed that the reinforcement scheme could effectively restrain the original crack growth of the steel bridge deck, and the bearing capacity of the steel bridge deck was significantly improved. Zhou et al. (2020) studied the above reinforcement effect, and the results showed that the reinforcement scheme proposed by Wang et al. (2021; 2020) had better effect compared with the reinforcement method of paving the upstream half of the deck with cold-mixed epoxy resin pavement and deck welding. Wang et al. (2020) used UHPC pavement structure to strengthen the deck of Tianjin Haihe Bridge. The case showed that no cracks appeared in the steel box girder within 2 years.

11 Advances in temperature field and temperature effects of bridge

11.1 Introduction

Bridges temperature field varies among their construction and operation stages, leading to considerable structural effects. The factors that cause temperature variation fall into three major groups: the effects of the environment such as solar radiation, heat transferring; actions in the construction process such as concrete hydration, steel welding; and accidental extreme cases occur during bridge operation, such as on fire or exploding. The research on bridge temperature in the year of 2020 mainly focuses on ambient temperature distribution and its effect, which will be reviewed as following.

11.1.1 Ambient temperature field of bridges

Accurately obtaining the ambitus temperature field of the bridge is the basis for further research on temperature loads and effects. Intense research has focused on temperature field testing and the thermodynamic boundary conditions required for numerical simulation.

The main research methods of bridge ambient temperature are on-site measurement and numerical simulation based on heat transfer theory. Yang et al. (2020g) and Shi et al. (2020b) carried out long-term on site tests, revealing the temperature field of CFST beams at high altitudes area. Leanne et al. (2020) calculated the temperature gradient of concrete box girder and composite beam in desert areas by long-term meteorological test data, finding out that the temperature of the steel is significantly higher than design value. Huang and Teng (2020) studied the sunlight temperature field of the maglev box girder by numerical simulation, considering the influence of wind speed. The results show that wind speed has a significant influence on the temperature gradients of the box girders. The temperature field of steel-concrete composite bridges draws more attention comparing with past years.

Many researchers have developed numerical stimulation models to get accurate bridge temperature field. Xiao (2020) through the measurement of a concrete box-girder bridge, found out a large difference between the measured radiation and theoretical radiation, and fitted the relation between the temperature gradient and solar radiation intensity. Zhang (2020b) proposed field finite element models that accurately consider the radiation with shading effects.

Besides the thermal boundary conditions, the complex factors such as bridge orientations, the painting, the shading effect, and the topography, increases the difficulty of simulations. Hence, some researchers developed the simulation method based on probability and statistics, which provides novel approaches and ideas for temperature field prediction. Tao et al. (2021), regarding the long-term environmental temperature field as a stochastic process with prescribed spectral and probabilistic properties, simulated a long-term temperature field based on limited monitoring data.

11.2 Ambient temperature action of bridges

To depict the effects of temperature field, temperature field decomposition is desirable. Most bridge design codes decompose the temperature field to the uniform temperatures along the longitude, the vertical and lateral temperature gradient along the bridge section. However, present research implies the inadequacies of temperature action in the current specification. Gu et al. (2020a) analyzed the temperature variations in the prestressed concrete box girder bridge based on measured data, and found the temperature gradient models of JTG D60–2015, AASHTO 2017, Bridge Manual 2013, and Eurocode1 all underestimated the temperature effects in the bottom slabs.

The research on the temperature action of steel-concrete composite bridges, long-span complex bridges, and the whole life cycle temperature action of bridges is in the ascendant. Jiang et al. (2020a, b) reviewed the research of temperature field and actions of CFST bridges. He proposed a temperature effects calculation framework for CFST members and trusses, and further prospected the problems of longitudinal temperature uneven distribution, temperature-induced steel-concrete interface debonding, and shading effect between components caused by the change of component inclination in CFST bridges. Fan et al. (2020b) proposed a numerical model to estimate the life-cycle temperature action of composite beam bridge based on reliability theory.

11.3 Temperature induced effects of bridges

Temperature induced effects of bridges mainly include the secondary stress, the temperature self-stress and the corresponding deformation, which have unexpected impact on bridge safety, durability and performance.

Recent research on temperature induced effect mainly focuses on structure safety and long-term performance, including beam bridge (concrete, steel and steel-concrete composite), arch bridge, suspension bridge, and other special bridge structures. The results further confirmed the temperature-caused damage to the bridge. Hossain et al. (2020) studied structural effects of temperature gradient on a continuous prestressed concrete girder bridge through field measurement and analysis. It was found that the cumulative effects of temperature and other long-term effects might make the tensile stress of concrete exceed the cracking limit. Honarvar et al. (2020) and Sawicki and Brühwiler (2020) studied the temperature-induced cambers and corresponding stresses of precast prestressed concrete beam and post-tensioned concrete box girder, finding that the stress on the extremely compressed fiber of the beam may exceed the stress limit during warm summer. Based on test temperature data, Wang et al. (2020g) evaluated the ambient temperature induced stress and displacement of a continuous steel box girder by FEM. The relationships between temperature action and girder displacements, reaction forces are summarized. Algohi et al. (2020) tested the variation of neutral axis of composite girder under ambient temperature field, and regressed the relationship between neutral axis and temperature of bridge web. It is found that the combined effect of steel-concrete composite beams during high temperature is weaker than that during low temperature. Taeb (2020) observed that a geosynthetic reinforced soil integrated bridge system (GRS-IBS) underwent cyclic straining of the superstructure, subjected to ambient temperature fluctuations. The bending of the upper structure will lead to the rotation of the footing, resulting in the periodic fluctuation of both the vertical pressure beneath the footing and the lateral pressure behind the end wall. Niu et al. (2020b) studied the temperature field and thermal effect of a concrete truss-arch composite bridge in V-valley, and discussed the influence of temperature action on the bridge local damage. Zhou et al. (2020h) explored the temperature-induced displacement of a suspension bridge, finding that the temperature of the cables plays a leading role in the vertical displacement of the girder and the horizontal displacement of the towers. The temperature equivalent length and the unified temperature-induced effect calculation formula are proposed and verified. Hu et al. (2020b) monitored the long-term longitudinal deformation of expansion joints for a suspension bridge. It is found that the temperature variation leads to the longitudinal displacement fluctuation of the expansion joint.

Temperature action can change constraint conditions and the material characteristics of bridges, thus affect its dynamic behavior. Jun Teng et al. (2020) studied the influence of the temperature effect on natural frequency of an arch bridge by correlation analysis, numerical simulation, and artificial neural network. The research shows that the arch's natural frequency varies according to elastic modulus, while girder's natural frequency varies according to the temperature-induced variation of elastic modulus and boundary conditions.

With the increasing requirements of serviceability, more and more bridges equipped structural health monitoring (SHM) system, which provides massive temperature data of bridge. How to separate the temperature effect from bridge total response became hotspot in recent years. Based on a steel truss bridge's SHM data, Zhu et al. (2020) studied the strain responses under various temperature actions. And the correlation between strain and temperature gradient was analyzed.

Eugene et al. (2020) presented damage indicators for small bridges and validated them by continuous recorded temperature data from SHM. Xia et al. (2020) proposed a model updating method based on Gaussian process (GP) metamodel. According to the thermal effect of bridge slab, the relationship between longitudinal boundary stiffness (LBS) and structural temperature is established. The range of LBS is approximately estimated by regression coefficient monitoring data and is used as the initial boundary for the subsequent updating process. GP metamodel is used to map the relationship between LBS and longitudinal displacement under thermal effect. The above research shows that bridge's performance degeneration caused by temperature action cannot be ignored. Separation of temperature effect in bridge SHM data to improve the effectiveness and reliability of health assessment is one of the current or future research hotspots.

12 Advances in numerical simulation of bridge structure

12.1 The numerical methods

With the economic development, bridge construction has made remarkable achievements in China. Thanks to the continuous progress of science and technology, the emergence of new materials and new construction methods, the bridge structure is developing in the direction of larger span and composite system, and the bridges across the sea or in mountainous areas under the complex geographical conditions are also emerging. All these need to master the mechanical state and behavior characteristics of the structure under various complex environments and actions before the bridge construction. The safety and the bearing capacity of the bridge structure in the construction process and operation stage need to be correctly evaluated. At present, the main problems of bridge structure are the static, vibration and stability problems in the elastic range, and the material nonlinear and geometric nonlinear problems in the inelastic range. To solve the problems, there are usually three ways: analytical method, numerical method and practical calculation method.

Material mechanics, structural mechanics and elastic theory are the theoretical basis of the analytical method to analyze the structure. The method is to deduce the analytical formula through certain assumptions on the basis of theory with high accuracy. But the analytical method is only suitable for those cases with simple structure and boundary conditions, regular and closed solutions. With the emergence and application of computer, the deepening of computational theory research and the growing maturity of computational methods, more and more problems can be solved with numerical methods in many fields of civil engineering. The most significant advantage of this method is that it can establish the accurate numerical model of complex structure under various actions and realize the numerical simulation analysis. The steps to solve the problem are easy to be implemented on the computer, with the characteristics of efficient, universality and high degree of automation.

12.2 Numerical model of beam

The cross-section size of the beam is usually much smaller than that of the longitudinal direction, so beam-column is the most favorable model in bridge structure analysis. There are several beam theories according to different assumptions of the displacement modes. Every beam theory can only provide approximate solution to the behavior of the spatial structure in some way respectively. Euler Bernoulli beam and Timoshenko beam are the most well-known classical beam theory based on The Plane Section Assumption which is applied in most structure analysis. But this assumption may lead to unneglectable error in the case of thin-walled beam due to the shear lag effect. So warping function was introduced in displacement field discarding the Plane Section Assumption in the conventional beam theory, but the warping function shows little definite physical interpretation. Moreover the shear-lag coefficient cannot reflect correctly the shear-lag effect and its variation along the axis of box girder. To circumvent this problem, an additional deflection function instead of the shear-lag function incorporated in the longitudinal displacement of the flange of the box girder is proposed, and variational principle is adopted to identify the undetermined constants in the longitudinal displacement function. Furthermore, the deflection, the additional deflection and their first derivatives are adopted as nodal displacement parameters in the box-girder elements to obtain the shape function of the element node displacement through the additional deflection function.

The deformation of the cross-section is evident for most thin-walled beam. Xiaoyuan Li proposed a new beam finite element method for the shear lag including shear deformation effects of thin-walled single and multi-chamber box girder of bridge structure (Li et al. 2021b). The cross section warping displacement is defined as five deformation modes, including shear lag warping displacement, initial shear deformation, bending, axial and correction mode. Numerical test has shown that this element has the advantage in calculation efficiency. Xiaoyang He proposed a new method considering axial equilibrium and shear deformation for overcoming the defect of the conventional method (He et al. 2020d). The longitudinal displacement of the web is used to satisfy the axial equilibrium condition and locate the neutral axis automatically. The shear deformation is evaluated based on the Timoshenko beam theory. Three independent shear lag functions are adopted for describing different shear lag intensities of the top, bottom and cantilever slabs.

12.3 Geometric nonlinear problems

Influences of geometric nonlinear effect have significant impact on structural mechanical behavior when span of bridge is getting longer, so considering large displacement effect is necessary in analysis. After decades of efforts, the geometric nonlinear theory of structure has made a great progress. In recent years, attention about geometric nonlinearity has focused on the fields such as: thin-walled structure, curved beam and composite material structure.

Wenxiong Li developed a new finite element model for nonlinear analysis of thin-walled beams which introduces a high-order interpolation for the warping displacement field allowing for the cross-section deformation (Wenxiong and Haitao 2020). The higher-order interpolation warping displacement function is capable of describing complex warping displacement distribution on the cross-section of thin-walled cross-section with significant coupling between bending and membrane deformations, and the distortion displacements are independently described by using a number of cross-section in-plane deformation modes. Numerical test results using proposed beam model can get accurate results even in the case of small wall thickness.

Erfan Shafei used a third-order shear deformation theory with a nonlinear von-Kármán strain field for anisotropic beams and combined with the advantages of the isogeometric framework (Shafei et al. 2020). The layup properties are assumed to be anisotropic in the depth direction and a transient tip follower force is considered. The effects of various important factors are studied with both h- and p- refinements. The difference of the nonlinear vibration and flutter characteristics between the anisotropic composite beams and orthotropic and isotropic ones are compared with this method.

H.A.F.A. Santos proposed two-layer composite beam structures with partial interaction with force-based finite element formulation for the buckling analysis which is based on Timoshenko theory with a single flexible shear interface (Santos 2020). The formulation relies on a hybrid variational principle of complementary energy involving force/moment as unknown variables, and the approximate field variables are selected to satisfy all equilibrium differential equations in strong form. The accuracy and effectiveness of the proposed formulation is demonstrated through several numerical tests.

12.4 Inelastic analysis

The most efficient model for inelastic analysis of the beam-column structure is the one-dimension fiber elements, in which the element is sub-meshed into longitudinal fibers. The geometric characteristics of the fiber are its location in local reference coordinate system and fiber area. This kind of element has been widely used in the nonlinear analysis of reinforced concrete structures, which has achieved satisfying results. Fiber model element is not only applied to the analysis of elastic-plastic problems of materials, but also has the advantage of calculation to solve some problems such as components with special structure and material defects. Giovanni used the fiber element based finite element method to evaluate the flexural performance of reinforced concrete jacket strengthened members (Giovanni and Gaetano 2021). He used a displacement-based beam element with two integral points for monotonic static nonlinear analysis through a fiber section beam element connected by nonlinear interface. Compared with the finite element results based on three-dimensional solid element, this method can greatly reduce the amount of calculation without loss of the accuracy considerably.

On the other hand, due to the change of displacement field caused by material yield, it is difficult to find a suitable displacement function to reflect the change of displacement field, so the force-based interpolation formulation is often used for nonlinear analysis, which has been proved to be easily convergent but complex. Pantò proposed an improved element of the Displacement-Based approach with adaptive displacement shape functions, which is called the Smart Displacement Based beam element (Pantò et al. 2019). This element is extended to include the axial force-bending moment interaction suitable for the analysis of reinforced concrete structures. The proposed extension requires the formulation of discontinuous axial displacement shape functions which are dependent on the diffusion of plastic deformations. The stiffness matrix of the extended smart element is provided explicitly and is dependent on the displacement shape functions updating.

The common failure modes of reinforced concrete bridge included joint shear hinging, bar-slip and bond failure, beam/column brittle shear damage, foundation failure and soft story collapses, in which joint is a critical zone of RC frame. Muhammad Shoaib Khan proposed a simplified beam-column joint modeling technique for the inelastic analysis of reinforced concrete frame structures (Shoaib et al. 2021). A zero-length link element with moment-rotation lumped plasticity hinge at the intersection of beam-column elements is used in this model, to simulate the nonlinear shear behavior of the joint panel. The backbone of the moment-rotation constitutive relation was obtained by using the empirical shear stress-shear strain relationship proposed by Kim and LaFave. The hysteretic response of the joint was simulated using the multi-linear hysteretic rule.

Inelastic cyclic local buckling may occur in steel beam-columns subjected to seismic loading, which leads to strain amplification within the locally buckled region. These local buckling should be paid attention in analysis for it will cause Ultra Low Cycle Fatigue or fracture. An approach is presented to estimate the evolution of local buckling induced strain at critical locations in steel wide-flanged members subjected to cyclic loading, which used a series of 26 Continuum Finite Element models (Yazhi and Amit 2020). The results indicate that the proposed method is a computationally efficient and capable of predicting the evolution of local buckling with minimal bias concerning to configurational parameters and loading history. A parametrized Timoshenko hysteretic beam finite element model with two-node elements is developed by M. Amir, New displacement interpolation functions are derived that satisfy both the exact equilibrium and kinematic conditions (Amir et al. 2020). The advantage of the proposed model is explained in detail and demonstrated through several numerical examples and comparisons with experimental data.

12.5 Constitutive model of materials

In recent decades, scholars all over the world have carried out a lot of research work on the constitutive model of concrete. Sargin first proposed the stress-strain curve of concrete considering the lateral restraint of stirrups on concrete deformation. Since then, Sargin's model has been improved with consideration of the lateral restraint of stirrups. The damage mechanics model of bridge structure is widely used in the research of earthquake and fatigue of bridge structure. The concrete damage model was first proposed by Lubline et al., and then Le et al. introduced the concept of stiffness recovery to improve the Lubline model. In order to apply the concrete stress-strain curve provided in the code for design of concrete structures to ABAQUS concrete plastic damage model, Li Qingfu calibrated the cut-off of concrete stress-strain skeleton and the value of damage factor, and studied the calculation method of model parameters and the value range of damage factor (Li et al. 2021a). The reliability of the cut-off point of stress-strain curve and the value of damage factor are verified by the comparison of experiment and numerical results.

High strength concrete is a new building material developed in recent years. Steel fiber reinforced concrete (SFRC) will show strong nonlinear behavior in the process of stress. Although there is not a recognized compression and tension elasto-plastic constitutive relationship for SFRC, researchers still carry out research work in this field. Changyong Li′s elasto-plastic constitutive model of concrete considers the influence of steel fiber characteristics (Li et al. 2020), and simulates the ascending part of the compression elasto-plastic constitutive curve with polynomial and descending part with rational fraction. According to the tensile test results of steel fiber reinforced concrete, the constitutive equation is established by using the characteristic parameters of steel fiber, and the parameters of steel fiber reinforced concrete are obtained by using the fiber spacing theory and the test data.

12.6 Mechanic degeneration of structure

Statistics on numbers of structurally-deficient bridges coupled with ongoing corrosion processes caused by deicing agents in many climates lead to a demand for better analysis techniques for corrosion-damaged reinforced concrete structural members. The corrosion of materials will not only increase the cost of operation and maintenance, but also threaten the performance and safety of bridges. In addition, rainwater corrosion in acidic environment for a long time is also the main reason for reducing the durability of the structure. Among those corrosion problems, chloride-induced corrosion of reinforcement has been recognized as one of the most predominant causes of structural degradation. The key to analysis of structural performance degradation is to establish an effective calculation model of concrete material performance degradation.

Chaoqun Zeng developed an analytical model to predict the mechanic behavior of a corroded steel bar. The model was established based on experimental data for slotted steel bars and electrochemically corroded steel bars (Chaoqun et al. 2020). The distribution of the corroded section was supposed to follow a lognormal function. The yield strength, ultimate strength and ductility of a corroded steel bar with different corrosion rates were predicted with the model. The numerical results agree well with the experimental ones.

Finite element analysis is an effective way to analyze the mechanic degeneration of bridge structures incused by corrosion. However, the FEA analysis requires many model parameters due to the long timescales over which corrosion occurs, which is infeasible to obtain through physical experiment. Le Huang gave a novel statistical approach using a neural network model to approximate these inputs based on data in the literature from 107 concrete members (Huang et al. 2020d). Load-deflection behavior resulting from numerical analysis with those predicted parameters shows good correlation when compared with available experimental data, confirming the accuracy of this method.

12.7 Numerical simulation in composite structure

The finite element method of composite beam based on beam element is a beam element model of composite beam first proposed by Newmark. Although most of those models have been built with Timoshenko beam theory, it is still an approximate model for composite beam structure. Higher-order beam theory is the most favorable modelling technique for an accurate prediction response of steel-concrete composite beams. The higher-order beam model is achieved with third-order variation of the longitudinal displacement over the beam depth for the steel and concrete layers separately. The shear studs are modelled for connecting the concrete slab with the steel girder as distributed shear springs along with the interface between these two material layers.

For the implementation of higher-order finite element formulation, the field consistent technique and full numerical integration of the stiffness matrix is carried out in order to avoid any shear locking and stress oscillation problem (Alabduljabbar et al. 2020). There are four different types of beam elements incorporated to develop models to observe an optimal number of beam element required for good convergence. The proposed model is assessed through validation and verification using existing published results and numerical results produced by detailed 2D finite element modelling of steel-concrete composite beams. The validation and verification show a very good performance of the proposed finite element models.

Curved composite box beams are subjected to coupled bending and torsion, so those beams are much sophisticated in numerical analysis compared with strait beams, especially curved composite box beams with wide flanges. Li Zhu proposed an efficient numerical simulation method of composite curved box girder element as a high-efficiency numerical simulation method (Uddin et al. 2020). This model can account for constrained warping, distortion, and the shear lag in concrete slabs and steel bottom plates, biaxial slip at the slab-girder interface and curvature differences along the width of the beam.

A high-efficiency finite beam element with 26 degrees of freedom (DOFs) is developed for curved composite box girders which accounts for constrained torsion, distortion, shear lag, biaxial slip at the interface and curvature differences along the width of the beam (Li et al. 2021e). Subsequently, two large-scale tests of a curved composite box girder are conducted and the findings are reported. A comparison among the experimental test results, elaborate FE model with shell elements and developed beam element shows good agreement. The force transfer behavior of curved box beams is further analyzed based on the proposed beam element, and the influence of the key parameters on the mechanical performance is investigated. In summary, this study contributes to the current literature with the development of a one-dimensional theoretical model for curved composite box beams and tests on curved box beams with a large curvature.

In order to analyze composite beam with local bucking effect, H.A.F.A. Santos proposed a force based nonlinear finite element method for buckling analysis of double-layer composite beams allowing for the local interaction (Santos 2020). The beam element has a single flexible shear interface which is modeled by Timoshenko theory. The mixed complementary energy variational principle with force and moment variables as basic unknown fields is adopted in the element derivation, and the approximate field variables are selected to make all the equilibrium differential equations satisfy the strong form. Lagrange multiplier method is used to realize the equilibrium between elements and Neumann boundary condition.

13 Advances in box girder and cable-supported bridge analysis theories

Bridge structural theories, such as theories of the box girder bridge with corrugated steel webs and traditional box girder bridge, middle tower effects of multi-span suspension bridge, and ultimate bearing capacity analysis of bridges, have been made a progress in 2020. It is seen that the innovation of bridge structural forms is still one of the most important sources to promote the technology revolution of bridge engineering. This section will introduce the above four aspects of the bridge structural theories.

13.1 Analysis theory of box girder bridges

13.1.1 Box girder with corrugated steel webs

For shear lag behavior Zhou et al. (2020a) proposed a modified bar simulation method for the shear lag of non-prismatic composite box girders with corrugated steel webs. The method is validated by the elaborate finite element model. Based on that, a parametric study is conducted to investigate the influences of the width-span ratio, girder height ratio and changing curve of girder height and loading form. Chen et al. (2020e) has conducted numerical and experimental study on two 1:5 scale composite box girder bridge with corrugated steel webs models, of which the truss is adopted as the bottom flange. Zhao et al. (2020b) adopted a spatial gird model to analyze the shear lag behavior of a cable-stayed bridge with hybrid girders, of which the section has five box cells consisting of the middle cell with the concrete webs and the other four cells adopting corrugated steel webs. The results show that the shear lag behavior is not significant.

For torsional behavior Zhang et al. (2020v) carried out experimental study on torsional behavior of two single-cell box girders with corrugated steel webs. Zhu et al. (2020f) conducted experimental and numerical study on 4 rescale torsional behavior of box girders with corrugated steel webs, of which the section is one chamber with multi-cells. The influences of the number of the box chamber and the spacing between the corrugated steel webs are investigated.

Zhou et al. (Zhou et al., 2019a, b, 2020c, 2021b, c) reported a series of studies on shear behavior of tapered box girders with steel corrugated webs. Particularly, they have investigated the resal effect, which is defined as that the shear internal force can be resisted by the inclined part of the axial force. Results show that the shear force may be overestimated if ignoring the resal effect. In addition, inspired by the forewing of Allomyrina dichotoma, Zhou et al. (2021b) proposed an improved corrugated steel web of which the turning points are reinforced. It indicates from a numerical investigation that the buckling behavior of the new corrugated steel web shows a better mechanical performance than the traditional one.

13.1.2 Traditional box girder

For shear-lag behavior Fan et al. (2020c) conducted an experimental and analytical study on the elastic flexural performances of steel-ultrahigh performance concrete composite box girders. The girder consists of a steel groove beam and an ultrahigh performance concrete deck. The proposed analytical model, which can consider the shear-lag effect, slide-shift effect and shear deformation of the steel web, is verified by the experimental and numerical results. The results indicate that to include the shear deformation of the steel webs in the analytical model can improve the calculation accuracy; He et al. (2020d) derived the calculation method for shear-lag of box girder based on virtual work principle; Yan et al. (2020e) investigated the bending behavior of the precast segmental concrete box girder and established a beam finite element model with 10 freedoms of degree.

For transverse load distribution coefficients Kong et al. (2020) proposed an improved formula for the transverse load distribution factor of multi-girder composite bridge based on the expressions recommended by ASSHTO. It is found that the proposed formula can bring higher accuracy.

In addition, there are literatures reporting the torsion behavior and failure of the concrete girder bridges. Such as, Li et al. (2020h) established finite element beam models for the single-cell and multi-cells box girder bridge. Wang et al. (2020a) investigated the failure of the bottom plate of a continuous rigid frame bridge by test in situation and numerical simulations, as a result, a reinforced scheme adopting steel plates is proposed for the bridge.

It can be concluded that the box girder theories have made a progress in 2020 and the research still focuses on the shear lag, torsional behavior and transverse internal force analysis of girder bridges. Thus, the refined structural theory of box girder bridge is one of the hot spot topics and may be further developed in the future, and new structural forms of the box girder with excellent performances are expected (Fig. 26).

13.2 Analysis theory of cable-supported bridges

13.2.1 Middle tower effect of multi-span suspension bridge

Multi-span suspension bridge is getting more concern as it is one of the optimal options for the sea bridge forms. However, the middle tower effect, which may lead to the buckling of the middle tower or the anti-slip between main cable and saddle, is one issue that restraints the applications of the bridge. The complexity of this issue involves determination of the stiffness of the tower and the anti-slip resistance between main cable and saddle. In the year 2020, the later got much of focus.

For double-cable multi-span suspension bridge, Zhang et al. (2020j) proposed a new saddle groove system, as shown in Fig. 27, and investigated the anti-slip safety of main cable through theoretical formula and numerical simulation. It is found that the double-cable multi tower suspension bridge is not restricted by the middle tower effect. Zhang et al. (2020k) investigated the friction characteristics of a 37-wire single strand using a verified numerical model, in which the beam element is used to simulate the steel wire and the solid element is used to simulate the saddle groove. The contact behavior between the steel wires is also considered. On the other hand, Zhang et al. (2020k) studied the layered sliding of main cable in the saddle groove by using a theoretical model. They also proposed a hybrid method for evaluating the friction resistance between main cable and saddle. This method includes variation of the main cable force along the arc length of the saddle groove. To study the lateral pressure characteristics between main cable and saddle groove. Wang et al. (2020m) proposed a discrete analytical model for calculating the lateral force of cable saddle system. The proposed method is applied to investigate the anti-slip behavior of the Taizhou Yangtze River Bridge. The analysis shows that the lateral friction can significantly improve the anti-slip resistance of the cable-saddle system. Cheng et al. (2020) derived the influence curve of tower stiffness on anti-slip coefficient and deflection span ratio of multi-span suspension bridge by finite element models.

It is concluded that to improve the anti-slip resistance between main cable and saddle, to propose novel saddle structural form and utilize additional friction force are very effective methods.

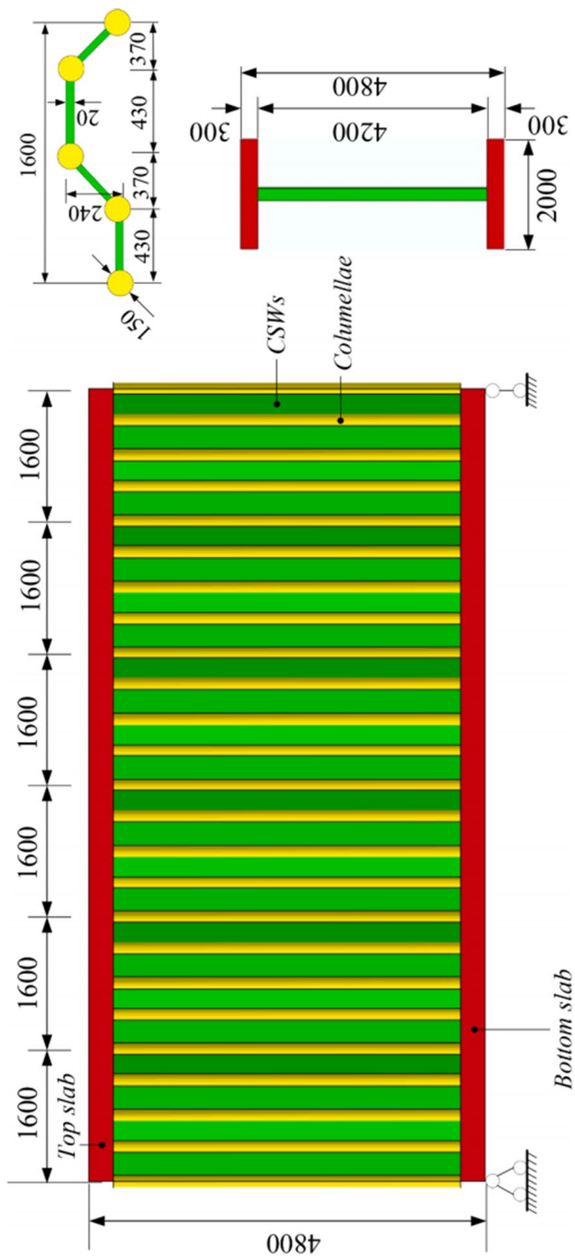

Fig. 26 The adapted corrugated steel web (Zhou et al. 2021b)

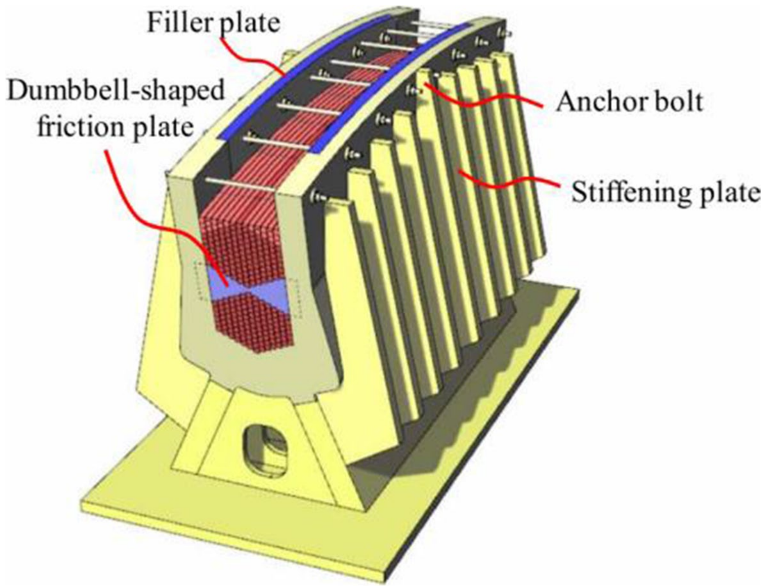

Fig. 27 The innovative saddle with dumbbell-shaped friction plate (Zhang et al. 2020j)

13.2.2 Ultimate bearing capacity of bridges

Huang et al. (2020e) adopted a solid finite element model for isolate concrete tower and a multi-scale finite element model consisting of the solid element and line element to analyze the ultimate bearing capacity of concrete tower for an earth-anchored suspension bridge. These finite element models have accounted for the plastic damage of concrete. The results clearly show the stress and damage state of concrete and rebars of the investigated tower. It indicates that the linear elastic ultimate load factor obtained from the multi-scale model is slightly larger than that of the isolated tower model, but the nonlinear ultimate load factor obtained from the multi-scale model is slightly smaller than that of the isolated tower model. Bai et al. (2020) has investigated the ultimate bearing capacity of middle tower for multi-span suspension bridge using a multi-scale finite element model shown in Fig. 28. Compared with the results obtained from the frame model, it is shown that the discontinue contact behavior of the connection between the tower segments can be ignored. Cui et al. (2020a) proposed an analysis method for stability of steel bridge tower under tanker fire scene. The example is illustrated by a multi-span suspension bridge - the Taizhou Yangtze River Bridge.

From the above investigations of practical bridges, the calculation models for the ultimate bearing capacity of cable-supported bridges are improved to obtain more accurate results. On the other hand, the evaluation of the ultimate bearing capacity of bridge under multi-field actions becomes a new topic, such as the ultimate bearing capacity of bridge under fire, which may further help develop the performance design of the bridge. The finite element model method is still the main methodology used for this issue, but more benchmark studies for different element models such as line element, shell element and solid element should be carried out in the future.

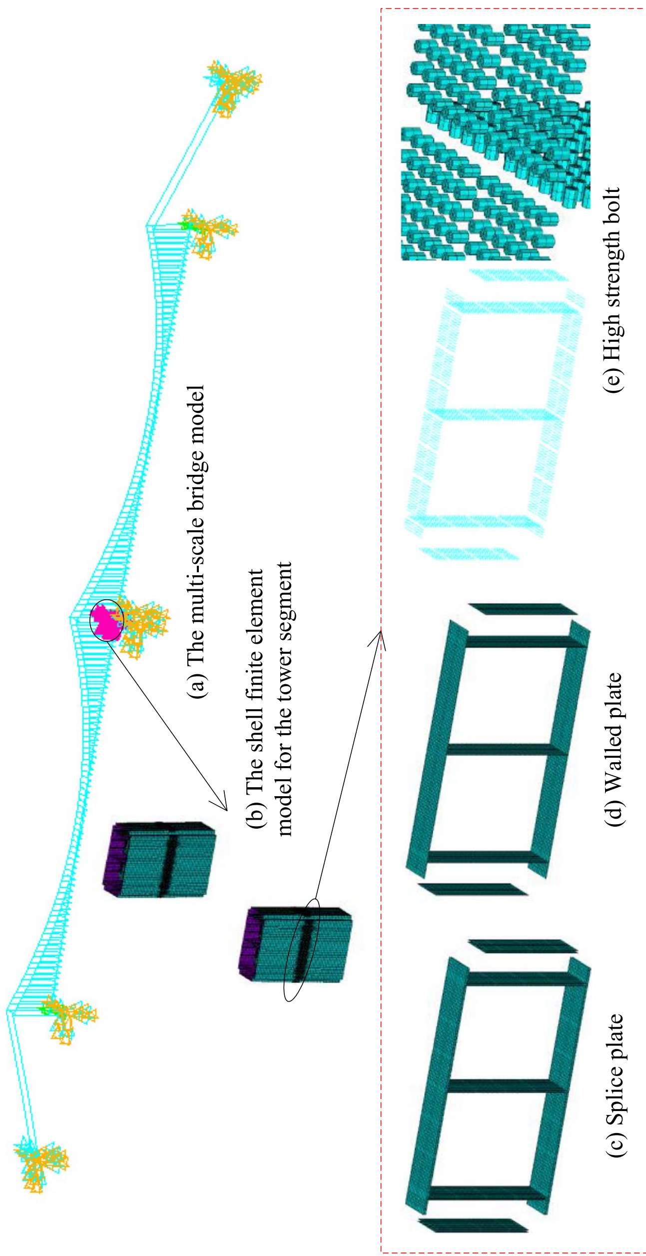

Fig. 28 The multi-scale finite element model for the multi-span suspension bridge considering the connection between tower segments (Bai et al. 2020)

14 Advances in bridge Informatization and intelligent bridge

Since the twenty-first century, a new round of scientific and technological revolution and industrial reform are emerging. The arrival of the digital age characterized by information and intelligence has promoted the development and innovation of bridge engineering. It is necessary to integrate cloud computing, big data, artificial intelligence, robotics and other emerging industrial technologies with bridge engineering to promote the industrialization, digitalization and intelligence of bridges from multiple dimensions such as intelligent design, intelligent construction, intelligent operation and maintenance. In this context, in order to further grasp the cutting-edge progress, this paper summarizes the cutting-edge technologies and important achievements in bridge informatization, intelligent detection, safety operation and maintenance, intelligent disaster prevention/mitigation and intelligent materials in 2020.

14.1 Bridge Informatization

Great progress has been made in bridge informatization and intelligent bridge in 2020. In the aspect of bridge informatization, Huang et al. (2020a) realized the 3D realistic modeling of the junction of bridge and tunnel in complex terrain based on the 3D tilt photography technology and BIM technology, which provided guidance for the selection of bridge location and the design of construction scheme. Fleischhacke et al. (2020) estimated the relationship between the deck performance of highway concrete bridge and the national bridge data based on Bayesian survival analysis, extracted the parameters leading to the deterioration of concrete bridge deck, and put forward the maintenance and reinforcement strategies. Duan et al. (2020a) established a bridge information model (BRIM) that can update the damage characteristics of Bridges in real time (Fig. 2), which more accurately reflects the current condition of bridges. In terms of bridge intelligent disaster prevention/mitigation, Zhang et al. (2020g) proposed an intelligent risk early warning and emergency response alarm system for railway Bridges in high and cold, difficult and complex mountainous areas. Mohammad et al. (2020) proposed a new hybrid model for predicting the peak flow of debris flow based on the artificial intelligence model (Bayesian network and support vector regression-particle swarm optimization) and the hybrid model of hydrological simulation system, which can be applied to the early warning system of debris flow and flood.

14.2 Intelligent material of bridge

Long span, light weight and intelligence are the development trend of bridges in the future, and the research and application of new intelligent materials are the key links. Shape Memory Alloy (SMA) is mainly characterized by shape memory and superelasticity, and has good fatigue and corrosion resistance. Liang et al. (2020a) developed a new friction-sliding bearing system using SMA cables. Ruiz-Pinilla et al. (2020) established the finite element model of Fe-based shape memory alloy (Fe-SMA) for external reinforcement of reinforced concrete beams, and proposed the analytical stress-strain curve of Fe-SMA. Shafei et al. (2020) studied the properties of superelastic SMA fiber and fiber reinforced polymer (FRP) composite reinforced steel bars. Karimipour et al. (2020) compared the effects of SMA and glass fiber reinforced polymer (GFRP) on the flexural and shear properties of reinforced concrete beams under different concrete compressive strengths. Optical fiber can be used in distributed optical fiber sensing system and is widely used in bridge detection and health monitoring. Rufai et al. (2020) embedded distributed optical fiber (DOF) sensors into glass fiber fabric layers for health monitoring of bridge structures throughout the whole life cycle. Yan et al. (2020a) proposed a new FRP anchor based on intelligent fiber grating (FBG). Piezoelectric materials can be used as sensing elements to detect the deformation of the bridge structure where the elements are located, and can also be used to make driving elements to change the stress state of the material and affect the structural deformation of the material. Based on the above researches, intelligent materials show unique advantages in bridge detection (health monitoring) and reinforcement, but the micro mechanics, coupling effect, material reliability and durability of intelligent materials need to be further studied.

14.3 Intelligent detection and safety operation and maintenance of bridges

There are many achievements in intelligent detection and safety operation and maintenance of bridges, which will be reviewed in detail in the following.

14.3.1 Intelligent detection technology of bridge

In the aspect of intelligent bridge detection technology, with the rapid development of the industrialization of aerial photography and remote sensing technology, the application of UAV in bridge detection has been widely concerned. Karim et al. (2020) used UAV equipped with mobile camera to carry out image acquisition on bridge, and realized the positioning and prediction of bridge cracks. Perry et al. (2020) proposed an intelligent detection system integrated with advanced data analysis tools (Fig. 29), which realized the identification of typical bridge diseases based on computer vision technology and machine learning through the images transmitted by UAV. Zollini et al. (2020) proposed an intelligent monitoring system for bridge diseases mounted on UAVs combined with object image analysis method (OBIA). Bolourian and Hammad (2020) realized intelligent detection of bridge structures through UAV equipped with LIDAR scanner and high-definition camera. Jung et al. (2020) proposed a UAV and bridge automatic monitoring technology based on real-time localization and map construction (SLAM) system. In the aspect of bridge detection robots, Boomeri and Tourajizadeh (2020) designed a climbing robot with self-adaptive control, which realized the high-altitude detection of bridge trusses and cables. Chen et al. (2020f) developed a crawling robot with multiple motion modes, which realized the comprehensive coverage of the area to be detected in the bridge. Baek et al. (2020) applied the sector scanning sonar technology to the underwater walking detection robot, and realized the three-dimensional visualization and high precision of underwater bridge detection. Dong et al. (2020) developed an automatic non-destructive welding seam detection robot based on structured light, which realized intelligent detection of welding seam condition of steel bridges. In terms of intelligent detection technology of ground penetrating radar (GPR), D'Amico et al. (2020) proposed a non-destructive detection system that integrated GPR and InSAR, and realized the detection of the infrastructure of railway bridge transition section. Alani et al. (2020) implanted the satellite remote sensing technology into the detection device integrated with GPR and InSAR to realize the determination of the masonry arch bridge structure and the precise location of structural connections. In

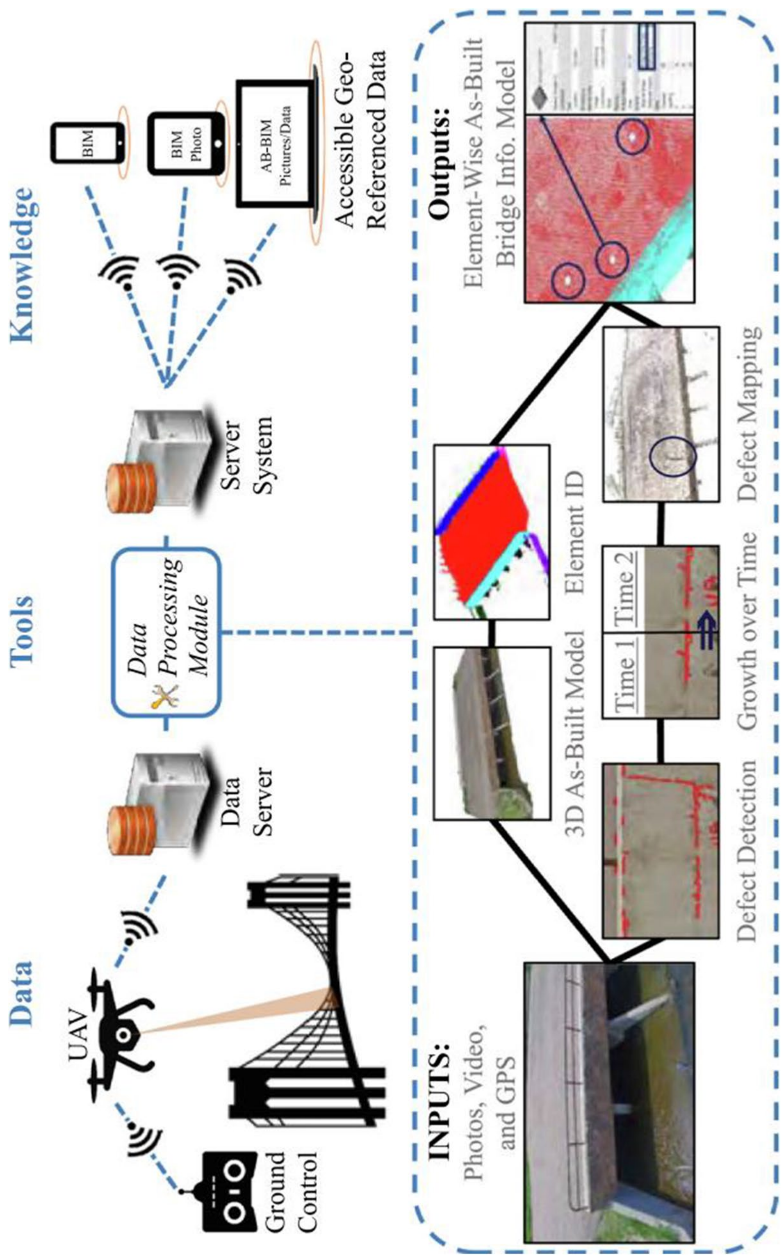

Fig. 29 Automated bridge inspection system based on UAV (Perry et al. 2020)

terms of new sensing technology, Zhang et al. (2020) designed an optical fiber sensor-cable force detection system for cable-stayed bridges, which improved the detection efficiency of cable force. Shao et al. (2020) designed a holographic vision sensor system and applied it to continuous monitoring of vibration response and deformation of bridges. In terms of other intelligent detection technologies, Liu et al. (2020i) introduced the AE phenomenon and the theoretical distribution of the shear stresses on a beam cross section, and tested 12 reinforced concrete beams using an AE system. Liu et al. (2020d) proposed an eddy current thermal imaging technology, which can be used to detect and evaluate steel corrosion phenomena in bridges. Wang et al. (2020c) designed a bridge inspection vehicle equipped with computer vision system, which realized the statistics of structural diseases and quantitative evaluation of the health status of the bridge.

14.3.2 Intelligent identification method of bridge

In the aspect of intelligent identification method of bridge, Li et al. (2020b) proposed a bridge crack extraction algorithm using full convolutional network and Naive Bayesian Data Fusion (NB-FCN) model to realize the identification of crack skeleton and boundary. Pham et al. (2020) proposed an intelligent detection technology for bolt loosening of truss bridges based on image recognition and deep learning. Kim et al. (2020) used 3D ground laser scanner to generate 3D point cloud, and combined with deep learning, carried out 3D point classification in each subspace to identify bridge components. Kalfarisi et al. (2020) proposed a crack detection and identification method based on deep learning, which detected cracks with bounding frames and realized intra-frame crack identification. Narazaki et al. (2020) proposed a visual-based automatic recognition technology for bridge components using images of complex scenes based on semantic segmentation algorithm. Bae et al. (2021) proposed a new deep super-resolution fracture network (SrcNet). Chen et al. (2020h) proposed a hierarchical Bayesian learning method based on sensitivity analysis to identify bridge damage with sparse features.

14.3.3 Intelligent evaluation and prediction of bridge

In the aspect of intelligent evaluation and prediction of bridge, Liu et al. (2020p) proposed the UAV track and camera strategy for bridge pier evaluation, and established a bridge pier crack evaluation method based on UAV and 3D scene reconstruction (Fig. 30). Gou et al. (2021) built a general bridge-track deformation mapping model, trained the mapping relationship between different bridge additional deformations and vehicle dynamic response, and developed an intelligent evaluation system for high-speed railway bridge traffic safety under complex service conditions. Tang et al. (2021) proposed a method of using convolutional neural network to realize the recovery of bridge health monitoring data, which realized the recovery of missing data with randomness in time and space. Wu et al. (2020e) proposed a modal Angle superposition method for estimating cumulative sliding displacement, and applied this method to the life prediction of a practical bridge sliding bearing. Ni et al. (2020) proposed a Bayesian method for state assessment and damage early warning of bridge expansion joints based on long-term massive monitoring data, which realized intelligent evaluation of bridge health conditions.

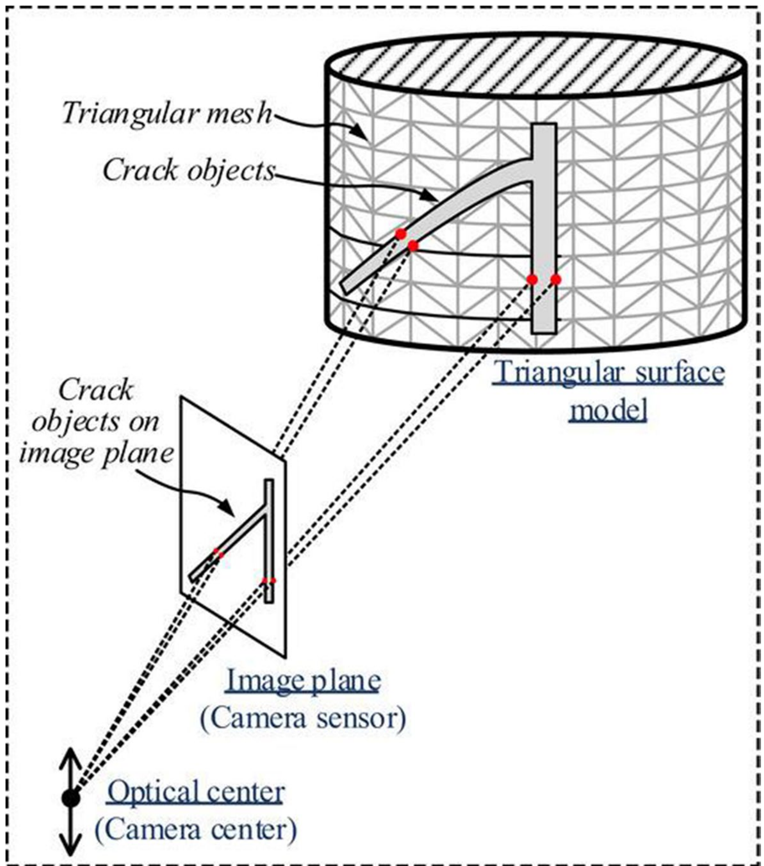

Fig. 30 Evaluation method of pier cracks based on UAV and 3D scene reconstruction (Liu et al. 2020p)

14.3.4 Intelligent maintenance of bridge

In the aspect of intelligent maintenance of bridge, Wei et al. (2020d) proposed a new automatic deep reinforcement learning (DRL) framework to obtain the optimal structure maintenance strategy (Fig. 31), which provided a general framework and optimal strategy for different structure maintenance tasks. Mao et al. (2020) established a multi-objective nonlinear programming model and studied the optimal maintenance scheduling strategy for bridge networks.

To integrate artificial intelligence and whole life cycle of bridge, and promote the development of national bridge engineering to the direction of safety, intelligence, green and long life, future research should grasp the golden age of transformation and upgrading development, continue to carry out theoretical innovation, technical research and engineering applications around the theme of "bridge informatization and intellectualization".

15 Advances in technology of bridge structure test

The bridge structure test is a method to obtain the real mechanical behavior of the bridge structure by applying static or dynamic action on the prototype or model of the bridge structure, so as to solve the problems existed in scientific research and design in

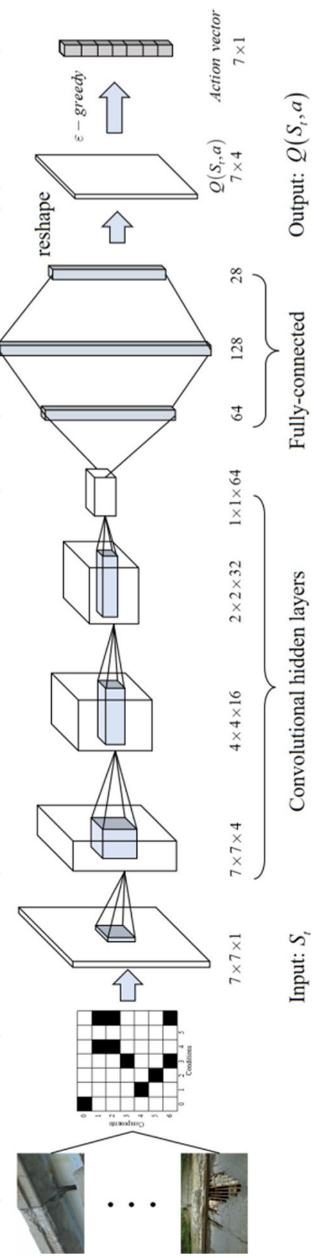

Fig. 31 The DRL architecture for the bridge deck example (Wei et al. 2020d)

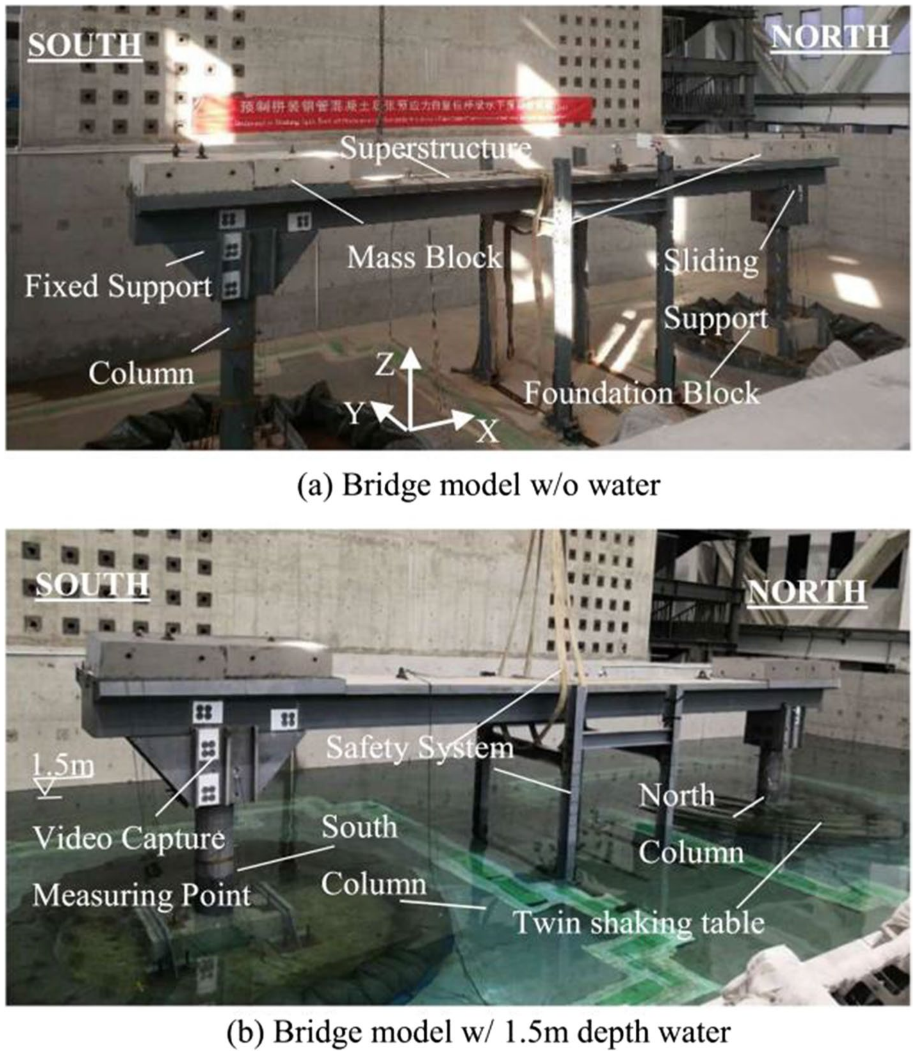

Fig. 32 Underwater shaking table test of a new self-centering segment of single span bridge

the field of bridge engineering. The research progress of bridge model test, bridge field test and measuring and test technology of bridge engineering in 2020 is reviewed, and some enlightening related researches are summarized. It is found that the technology in bridge structure test is further developing towards the general direction of multidisciplinary integration.

15.1 Bridge model test

15.1.1 Static model test

Static load test is one of the most commonly used test methods in bridge structure test. The bearing capacity, force transmission mechanism, and safety degree of bridges under static load can be determined by static load tests. The representative progress of static load test in 2020 is as follows. In the bending test of curved round concrete-filled tubular flange girders (CRCFTFG) and the corresponding curved I-girder (CIG), Gao. (2020)

designed a special rolling track device (RTD) to ensure that the load direction is vertically downward. Hassan (2020) innovatively proposed a pure torsional load test method, which ensured the stress on the beam was purely in a torsional mode.

15.1.2 Dynamic model test

The dynamic model tests mainly include: pseudo-static test, pseudo-dynamic test, shaking table test, wind tunnel test, etc. The current research progress includes: Lin et al. (2020a) proposed a collapse prediction method for long-span cable-stayed bridges based on shaking table test and nonlinear finite element model modification. By conducting underwater shaking table tests, Zhang et al. (2020a) studied the seismic performance of precast segment structures of bridge in high seismic risk areas and complex water-rich areas, as demonstrated in Fig. 32.

15.1.3 Fatigue test

A typical development in fatigue testing is the emergence of fatigue tests that take corrosion into account. Xue (2020) designed a method of accelerating corrosion in the test to study the corrosion fatigue failure of high strength steel wire, as shown in Fig. 33.

15.1.4 Other model tests

Other model tests mainly include flume test, fire resistance test, temperature test, and electric corrosion test. It is worth mentioning that new ideas have emerged in the approach of making experimental models, Brito (2020) developed a low-cost bidirectional excitation friction sliding system to improve the seismic performance of reinforced concrete bridge piers. The sliding model was made by using a 3D-printed mold, as shown in Fig. 34.

15.1.5 Brief summary

Nowadays, the development of bridge model test has the following characteristics: (1) the diversity of the model test forms; (2) The scale of model test gradually increased;(3) Advances in model manufacturing processes;(4) Optimization of test conditions;(5) Complications of loading forms: The coupling of complex environment and the combined action of multiple load types are concerned;(6) The application of real-time model modification technology.

15.2 Bridge field test

At present, the development of bridge field test technology shows an obvious trend of multidisciplinary integration and has made great progress. The following will be a detailed review. Kim et al. (2020) proposed an image-based back analysis method to calculate the cable tension of a suspension bridge using a non-contact indirect method. Zhang et al. (2020a) developed a ground-based microwave interferometric radar system and carried out field tests on a long-span suspension bridge, and a method that uses three reference points to measure the bridge girder displacement was proposed. To verify the applicability of deformation area difference (DAD) method for localization of damages in bridge structures, Erdenebat (2020) conducted an in-situ test on a

Fig. 33 Fatigue test of steel wire and salt spray chamber

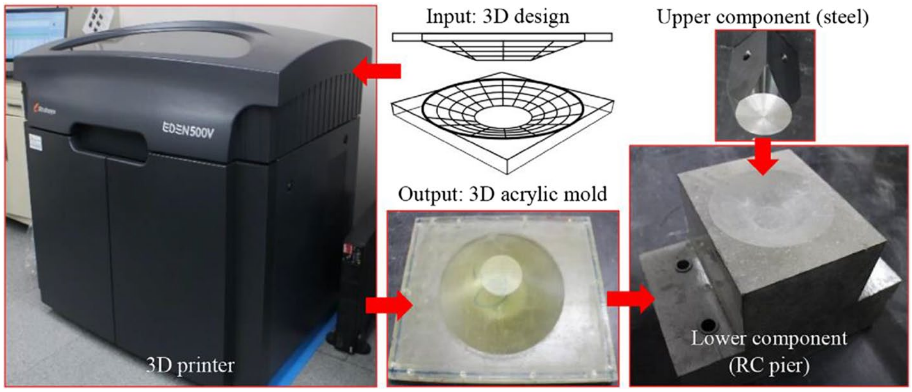

Fig. 34 3D printer and printed test mold

Fig. 35 Locating target and testing UAV

prestressed concrete slab bridge, with close-range UAV photogrammetry to measure of structural stiffness changes and damage, as shown in Fig. 35.

15.3 Measuring and test technology of bridge

With the development of equipment and data processing technology, bridge detection is more and more advanced and scientific. The new bridge detection technology, which is mainly based on non-contact testing method, has made great progress. Tian (2021) proposed a non-contact cable force estimation method based on UAV and computer vision technology. Lee (2020) proposed a Long-term displacement measurement of full-scale bridges using camera ego-motion compensation. It is worth noting that Dong et al. (2020) proposed a new deep learning-based full-field optical flow method for measuring structural displacement, which has higher accuracy than the traditional optical flow

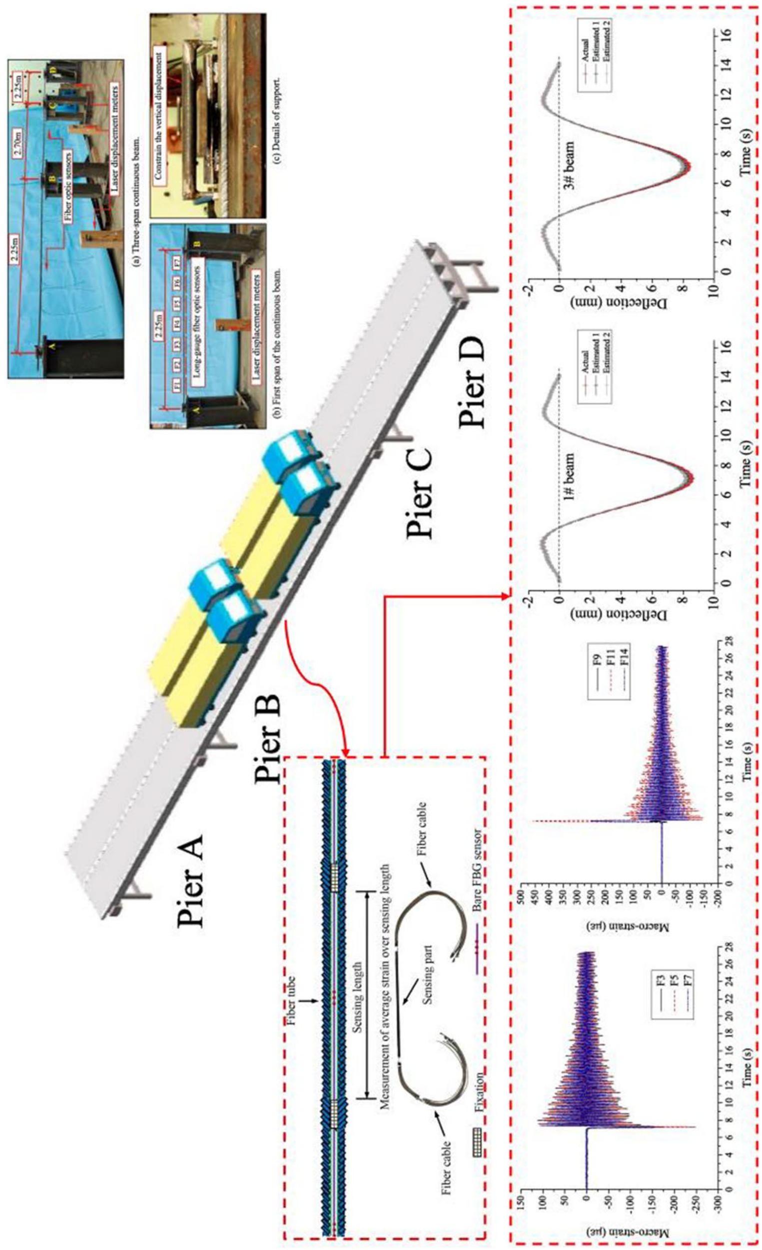

Fig. 36 Displacement shape measuring method of continuous beam bridge based on long diameter optical fiber sensors

algorithm. Hong (2020) proposed a no-reference point method for monitoring the displacement shape of continuous girder bridge by using long-diameter optical fiber sensor, which can accurately monitor the displacement time series of each section, as shown in Fig. 36.

With the improvement of bridge testing requirements, non-destructive testing techniques such as ground penetrating radar, scanning electron microscope, CT methods have been gradually applied in measuring and test technology of bridge. Such as Larsen (2020) designed a novel multi-channel, automated, echo detection device that can be used to distinguish between complete concrete and layered concrete. Simultaneously, the application of big data, data mining technology, deep learning technology and cloud computing technology has greatly improved the efficiency of bridge detection. For example, Perry et al. (2020) proposed a holistic inspection system that combines UAV field inspections with advanced data analysis tools, which provided a more convenient decision-making system for bridge managers, as shown in Fig. 29.

16 Advances in bridge assessment and reinforcement

Due to the contradiction between the construction needs brought by the early economic development and the backward technical reserve, there are many security risks in the operation stage of the subsequent bridges. Between 2007 and 2012 alone, 37 bridges collapsed, killing more than 180 people. Nearly 60% of them were built after 1994 and were less than 20 years old. However, about 40% of the bridges in China's highway network are more than 20 years old at present. According to the current data, in the next 10 to 30 years, China will face increasing pressure of bridge inspection, evaluation and reinforcement.

Bridge maintenance has been upgraded from economic level to social level. In recent years, researchers have devoted themselves to the study of bridge health assessment and reinforcement. Based on the latest research progress in this field, this paper summarizes contents from bridge monitoring technology, advanced sensor technology to bridge evaluation theory, bridge reinforcement methods and strategies, which can be used as reference for future research and engineering practice.

16.1 Bridge health monitoring technology

Bridge health monitoring is to make every effort to carry on automatic and normal monitoring to each index parameter, mainly in order to realize the real-time monitoring and early warning, For the purpose of this requires, a lot of monitoring methods and equipment are required as technical supports. The following mainly introduces the research progress of the monitoring technology of main bridge diseases, advanced sensor and corresponding signal processing.

16.1.1 Monitoring technology for main bridge diseases

For steel corrosion, electrochemical technology is usually used for monitoring, such as open potential, linear polarization resistance, electrochemical impedance spectroscopy, etc. (Xu et al. 2020a). This method is also adopted in the current detection technology standards at home and abroad (Materials 2015; Ministry of Construction of the People's

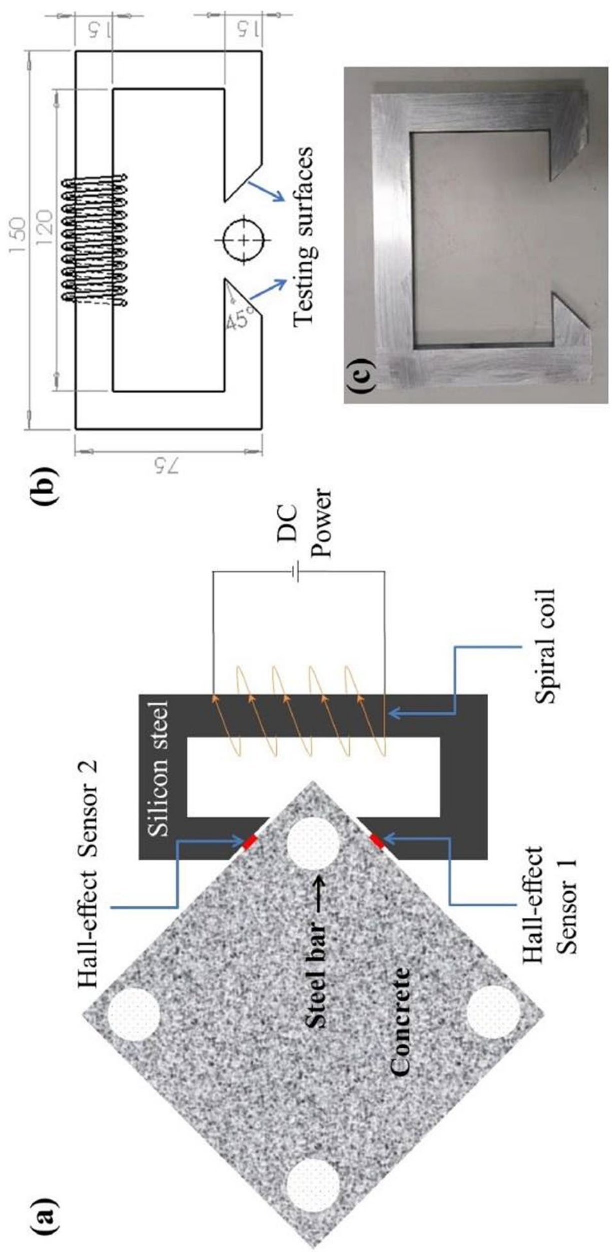

Fig. 37 Schematic diagram of external electromagnetic (EM) sensor

Republic of China 2019), and new progress has been made in the study of electrochemical detection methods: Samson et al. (2020) designed a new probe based on the constant current polarization method, which was used to measure the corrosion rate of steel bars. Thunyaluk et al. (2020a) used electrochemical current noise method to measure corrosion of steel bars. Li et al. (2020a) conducted theoretical analysis and revealed the corrosion potential properties under different corrosion states and the relationship between the corrosion rate and the corrosion potential.

Recently, researchers also devote themselves to the development of physical methods for steel corrosion monitoring, among which electromagnetic methods based on Hall effect are more widely studied. Fu et al. (2020) developed an electromagnetic device that can be placed on reinforced concrete structures (as shown in Fig. 37) to detect and monitor the corrosion of embedded steel bars. Mosharafi et al. (2020) use T-test, F-test and other statistical analysis methods to study the reliability of steel corrosion magnetic recording. The results show that the method based on data standard deviation is the most reliable. Azari et al. (2020) developed a bridge steel corrosion robot based on the magnetic flux leakage method. The robot system has been evaluated by testing the model beam in the laboratory, and the results show that the system can successfully reveal the magnetic flux leakage signal in the corrosion zone.

Although there are many advances in other physical monitoring methods, such as reinforced concrete corrosion detection method based on eddy current thermal image (Liu et al. 2020d), reinforced concrete corrosion quantitative image processing technology based on ground penetrating radar data (Zaki et al. 2020), embedded reinforcement crack and corrosion monitoring technology based on piezoelectric ultrasonic sensor (Liu et al. 2020e), etc.. However, the authors believe that the electromagnetic monitoring method based on Hall effect has a wider application prospect.

For concrete durability monitoring, resistivity method is usually adopted. The latest progress mainly focuses on optical sensing detection technology, among which the research progress of fiber grating sensor is particularly prominent, which will be specially introduced later.

16.1.2 Sensor technology

In the field of bridge health monitoring, various types of sensors have been validated for their applicability. Sensors used in bridge monitoring are always expected to be diversified and integrated to cover increasingly rich monitoring contents. Fiber grating sensor has high precision, which can meet the precision requirement of aviation and spacecraft monitoring (Kwon et al. 2020). Its working principle and carrying form are shown in Fig. 38. Recently, fiber Bragg grating sensors have made outstanding progress in various aspects of bridge monitoring.

In the aspect of reinforcement corrosion monitoring, Tang et al. (2020) used long-period fiber grating sensors to monitor the pitting passivation, initiation and expansion of steel bars. Wang et al. (2020d) used fiber Bragg grating (FBG) to detect the corrosion rate of steel bars in concrete of different strength levels, and the sensitivity reached 0.02% and the monitoring range was more than 1%.Huang

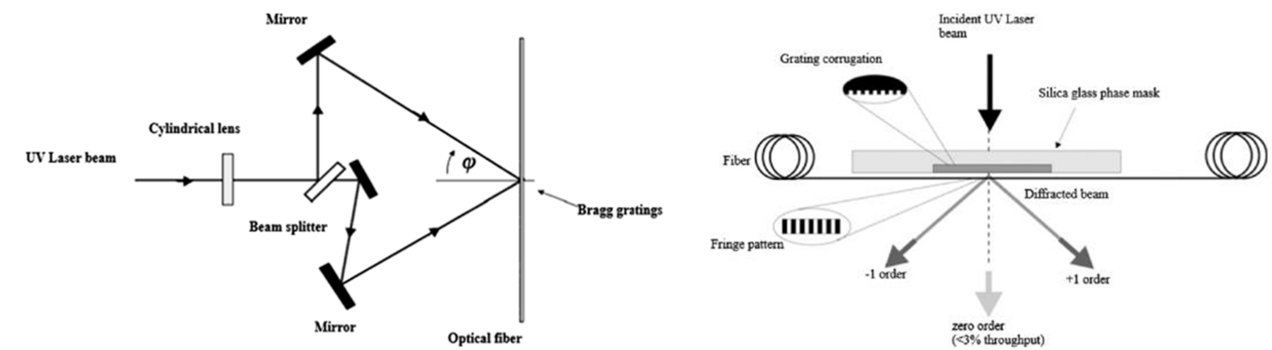

Fig. 38 Mounting form and principle of fiber Bragg grating sensor. **1** Principle of interferometry. **2** Principle of phase mask technology

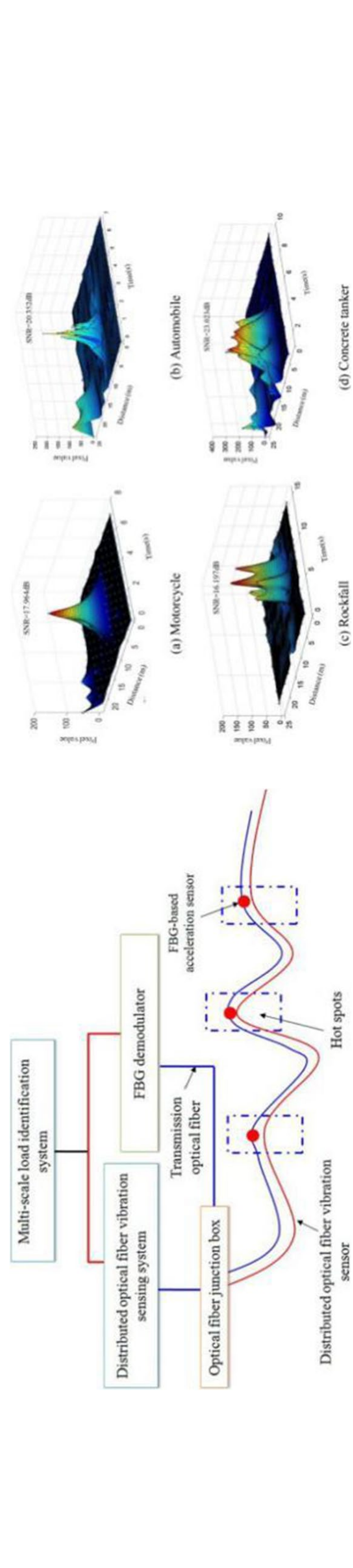

Fig. 39 **1** Mounting form. **2** Test result

In terms of load monitoring, Zhang et al. (2020i) proposed a multi-scale load identification system based on distributed optical fiber and local FBG vibration sensors, which realized the measurement of vibration loads on full-size structures and hot spot location, and reached the level of accurate identification of rockfall impact. Its carrying form and test results are shown in Fig. 39.

In addition, FBG sensors also have many advantages in monitoring pile top displacement and lateral resistance (Wang et al. 2020e), seismic monitoring (Zhou et al. 2020e) and other aspects. Besides, there are also many research advances in the design and manufacture of fiber Bragg grating sensors (Lee and Lee 2020; Zhang et al., 2020s), demodulation equipment (Liu and Schumacher 2020; Wang et al. 2020e), fault identification (Liu et al. 2020b; Peng et al. 2021) and other aspects, which will not be discussed here.

16.2 Bridge health assessment

Bridge health assessment can be roughly divided into two categories: one is based on the time-varying reliability theory, which focuses on exploring the logic and facts of "the relationship between structural state and a series of variables", trying to actively select the appropriate reliability index and give it weight through strict theoretical derivation or sufficient experimental evidence. To a certain extent, it is the continuation of the design concept; The other is the evaluation method based on historical measurement data, which recognizes the uncertainty of "the relationship between structural state and a series of variables", and achieves the purpose of evaluation and prediction by other means (such as artificial intelligence). There has also been some progress in the joint application of the two methods (Li et al. 2020g; Mankar et al. 2019), which will not be expanded here for the time being. And the above two methods will be mainly introduced.

16.2.1 Evaluation method based on time-varying reliability theory

The evaluation method based on the time-varying reliability theory is actually based on the existing theory and experimental results to carry out the probability "scan" on the structural state in time. When some adverse factors are believed to occur at the same time with an unacceptable probability, they will be given appropriate indicators and weights, and combined analysis will be carried out. For example, Zhuang and Miao (2020) established a simplified finite element model satisfying the accuracy of fatigue analysis by using the comprehensive framework of reliability analysis, and calculated the fatigue reliability of the hanger with or without corrosion by Monte Carlo method. Pietro et al. (2020) investigated the influence of steel corrosion on the time reliability curve of reinforced concrete structure through cluster analysis based on Gaussian mixture model.

In addition to the above research progress in the evaluation methods based on time-varying reliability theory, there are also research progress in the evaluation methods of progressive random processes (Gong and Frangopol 2020; Koteš et al. 2020; Yu et al. 2020) and emergent random processes (Jin et al. 2020; Yan et al. 2020d), which will not be expanded here.

16.2.2 Evaluation method based on historical measurements

The evaluation method based on historical measurement data is actually based on the existing measurement results to carry out a time series 'scan' on the probability distribution of the structure state. When an adverse factor is 'considered' to have a certain temporal correlation with the probability distribution of a certain state of the structure (such a judgment may be artificially subjective or machine-made), it is given a corresponding weight. Such 'scanning' means include Bayesian, artificial neural network and other methods.

Based on the data collected from visual inspection and ground penetrating radar (GPR) technology, Mohammed et al. (2020) used the K-means clustering technology based on unsupervised learning algorithm to determine the scoring threshold of the bridge state. Dorafshan et al. (2020) developed and trained the convolutional neural network by using the impact echo measurement data of the simulated test blocks of concrete-asphalt bridge deck with artificial defects, and used DLMS to generate an accurate map of the defects. Liu et al. (2020f) compared and analyzed the prediction accuracy of BP neural network and RBF neural network in the seismic performance evaluation of pier columns, and the results showed that the prediction effect of RBF network was better than that of BP network.

16.3 Bridge reinforcement strategy

Bridge maintenance and reinforcement includes bending reinforcement (Gao and Sun 2020; Guo et al. 2020b; Tayeh et al. 2020), shear reinforcement (Abadel and Albidah 2020; Cladera et al. 2020; Wei et al. 2020a; Zheng et al. 2020d), seismic reinforcement (Jia et al. 2020c; Zanini et al. 2020; Zhou et al., 2020g), etc.. Limited to space, this paper focuses on the research progress of reinforcement strategy.

The network-level strategy focuses on the identification of bridges in the network that need to be strengthened and the allocation of reinforcement measures. Michael et al. (2020) proposed a method to determine the basic reinforcement requirements of concrete Bridges. In this method, the horizontal frequency diagram is adopted, the risk matrix is considered, and the risk number is adopted to evaluate the evaluation attributes of stability and durability respectively, and finally to determine which types of bridges in the network need to be strengthened. Yang et al. (2020) proposed a non-simulation method based on the risk boundary of degraded bridge network, which used system reliability analysis to determine the occurrence probability of various bridge failure situations in the network. For each failure situation, traffic distribution was carried out to predict the traffic in the damaged network and the network level consequences. Then the upper and lower bound of the network level risk is given, so that only a small number of traffic allocation operations can be carried out efficient and accurate risk assessment. Finally, the optimal life-cycle maintenance plan, including the maintenance plan and the investment of each maintenance can be obtained through meta-heuristic search.

The project-level maintenance and reinforcement strategy focuses on determining the target reliability of the bridge to be strengthened. Zhang et al. (2020t) proposed a method for selecting the reliability index of steel box girder of cable-stayed bridge based on the objective of optimal structural parameter ratio. The reliability index of main cable flexural bearing capacity and main cable flexural strength of cable-stayed bridge is calculated by finite element method. The reliability index under different structural parameter ratio and the relationship between reliability index and structural parameter ratio are obtained by data fitting, Then the optimal structural parameter ratio is calculated from the perspective of cost and benefit. Finally, the optimal structural parameter ratio is substituted into the relationship between reliability index and structural parameter ratio to obtain the optimal reliability index. Wang (2020) and others for index properties of reinforcement scheme of the system complexity, the range and uncertainty characteristics, such as how to use the theory of rough set theory and game decision of Minimax decision-making algorithm optimization idea, consider emergency reinforcement scheme and ideal scheme between the dominance and its properties of probability measure and equivalence relation between each scheme attribute value, the weight of the index is determined by using the attribute superiority relation.

17 Advances in prefabricated concrete bridge structures

17.1 Prefabricated assembly of the superstructure

17.1.1 The new form and new structure of the prefabricated assembly connection of the superstructure

Prefabricated concrete bridges have been widely used in bridges due to i) high efficiency and convenience, ii) low environmental interference, and iii) high engineering quality. The superstructure connection has a significant influence on the performance of the prefabricated concrete bridge, and it is the research interest of the superstructure prefabrication assembly.

Peng et al. (2020) proposed an integrated precast steel-concrete composite girder bridge for small and medium-span bridges. The mechanical properties and construction technology of this precast steel-concrete composite girder are superior to the traditional split precast steel-concrete composite beams. Di et al. (2020) designed two new types of U-shaped rod joints: rectangular joints with stainless steel ties and T-shaped joints. The details of the T-joint effectively increase the maximum loading at cracking and control the development of interface cracks.

The use of the above-mentioned new connection technology extends the scope of use of prefabricated bridges. However, the performance degradation and control measures of the connecting device or structure need to be studied in the complex service environment.

17.1.2 Strength of prefabricated assembly connection of superstructure

Ensuring that the prefabricated assembly connection has sufficient strength is the basic requirement for the performance of the prefabricated assembly bridge. The strength of the prefabricated connection is closely related to the connection structure.

Yang et al. (2020d) produced and tested ten push-out specimens of bolt shear connectors and studied the influence of the arrangement of multi-bolt connectors, bolt spacing and local reinforcement of reinforced concrete on shear performance. Yao and Yan (2020) proposed a UHPC wet joint scheme and carried out optimization and stress performance research to improve the problem of easy cracking and damage at the joints of prefabricated UHPC bridges due to discontinuous steel fibers. Guo et al. (2020a) carried out 21 groups of experiments to investigate the ultimate bearing capacity and load-slip characteristics of the bolt-shear connection and established an effective finite element model. Zhao et al. (2020) revealed the use of room temperature curing to study the steel-ultra-high performance concrete composite bridge slab and found that the deformation of the composite bridge slab has stabilized when the NC-UHPC age is about 28 days. He et al. (2020) designed a bridge deck with unreinforced ultra-high performance concrete as the pavement layer, and they found that using the glue joint method is more convenient because the bridge deck has better ductility and high bearing capacity. In order to improve the cooperative force performance of the composite bridge deck, Cai (2020) proposed a new type of steel-UHPC composite bridge deck structure based on steel pipe connectors. Hou et al. (2020) examined a new type of fully assembled steel-concrete composite beam, and studied the influence of different steel channel forms, cyclic loading, and the number of fasteners on the shear performance of composite beams.

With the development of high-performance concrete, high-strength steel and new structural glues, the traditional connection structures have been significantly enhanced, and some new connection structures have also been realized. The durability of components has also been improved. However, there is still a lack of research on the durability of nodes using these new materials, which is the focus of further research.

17.1.3 Normal use performance of the prefabricated assembly connection of the superstructure

The performance of bridges will be degraded due to the increase of urban traffic volume and the working life of bridges. The requirements of safety, applicability and durability will no longer be met. In order to maintain the normal performance of the bridge during the service life, improving the safety and applicability is an important research direction in the current directions.

Al-Rousan (2020) studied that under different prestress levels, full-height precast concrete bridge decks can maintain their integrity under 8 times the AASHTO load without significantly reducing their final strength and stiffness. Honarvar et al. (2020) researched the relationship between the temperature gradient of precast prestressed concrete beams with regional and meteorological seasons and gave corresponding correction coefficients.

17.1.4 Durability of prefabricated assembly connection of superstructure

The current bridge design takes into account the high bearing capacity of the bridge. However, in the use of bridges, durability and bridge scale are less considered. Therefore, it is important to enhance the durability of the bridge structure during the bridge service life.

Mager and Geißler (2020) proposed a new calculation method for the problem of the formation of aggregate cracks in the fully prefabricated composite beams. The new method can be used to calculate the cumulative cracks and bearing capacity. Liu et al. (2020) used UHPC in the negative bending moment zone that can effectively solve the problem of cracking.

17.2 Prefabricated assembly of substructure

As the main load-bearing component of the bridge, the substructure of the bridge has always been the focus of bridge design and construction. Compared with the prefabricated assembly of the superstructure, although the development of the prefabricated assembly process of the substructure is relatively late, with the increase in the demand for prefabricated piers in bridge engineering in recent years, the consideration on prefabricated piers has been gradually increased.

17.2.1 Seismic performance of substructure prefabricated assembly connection

As one of the bearing members of the bridge structure, the pier has a vital influence on the overall performance of the bridge. The strength of the connection of prefabricated bridge piers is the key factor that affects the bearing capacity. The research and development of the connection technology and performance improvement of prefabricated pier columns are the primary issues in the study of prefabricated bridge piers.

Wang et al. (2020) proposed a new connection method using lapped large-diameter steel bars and ultra-high performance concrete grouting. Liu et al. (2020k) studied the influence of grouting sleeves on the seismic performance of bridge piers at different positions. Jia et al. (2020a) improved the seismic performance of the pier column by installing elastic gaskets in the plastic hinge area. The main seismic indicators of the precast concrete piers are similar to those of the cast-in-place piers, and it effectively reduces the local concrete damage at the bottom of the bridge column. At the same time, it also increases the energy consumption capacity. Shafieifar et al. (2020) proposed an alternative connection method of prefabricated cap beams and pier columns. This connection method is suitable for seismic and non-seismic areas and can achieve sufficient ductility. Zhang et al. (2020c) studied the seismic performance of a new self-centering segmented concrete-filled steel tube column pier with a good self-resetting ability under strong earthquakes. Jia et al. (2020b) found that self-resetting prefabricated segmented piers have good ductility and good self-resetting ability in the direction orthogonal to the load.

17.2.2 Normal performance and durability of substructure prefabricated assembly connection

The bridge pier is an important structure for carrying the load on the upper part of the bridge. The capacity of the bridge pier is important because the deformation of the bridge piers will cause the superstructure to produce structural secondary internal forces, which results in a decrease in the bearing capacity of the structure and even damage to the structure. Therefore, the performance of the substructure prefabricated assembly connection is also a hot research issue.

Ahmadi and Kashani (2020) used the finite element model to study the nonlinear static and dynamic characteristics of prefabricated post-tensioned bridge piers. In order to better understand the impact of insufficient grouting defects, Zheng et al. (2020b) studied the mechanical properties of grouting sleeves with predetermined vertical grouting defects. Since the diameter and the spacing of the connecting steel bars of grouting corrugated pipes are generally small, it will also cause certain difficulties in construction. Therefore, Fan et al. (2020d) proposed to use large diameter steel bars to connect grouting corrugated pipes. Both precast piers and cast-in-place piers show similar lateral resistant ability.

With the application of prefabricated bridge piers in high-cold and highly corrosive areas, some researchers have also carried out research on the durability of substructure prefabricated joints.

Moradian et al. (2015) studied the durability of bridge pier structures constructed with prefabricated post-tensioned high-performance concrete box girder in the marine environment. According to the test results, a method of repairing the bridge pier structure is proposed.

18 Conclusions and prospects

The paper reviews some advances in bridge engineering in 2020, including concrete bridge and high-performance materials, steel bridges, composite girders, bridge seismic resistance, wind resistance of bridge, train-bridge coupling vibration research, bridge hydrodynamics, the durability of the concrete bridges, fatigue of steel bridge, numerical simulation of bridge structure, box girder and cable-stayed bridge analysis theories, bridge informatization and intelligent bridge, the technology in bridge structure test, bridge assessment and reinforcement, temperature field and temperature effect of bridge, prefabricated concrete bridge structure. Conclusions and prospects for these aspects are listed as follow.

18.1 Concrete bridge and high-performance materials

One can continue to carry out and improve the research on the spatial shear mechanical behavior of concrete structure, and further develop the discrete element simulation method; more in-depth research on bridge management and maintenance; increase the research on the coupling of concrete bridge structure and higher dimensional extreme environment. In the future, concrete materials will continue to develop towards high mechanical properties, green environmental protection and intelligence. Special functional concrete has been developing rapidly with the support of interdisciplinary cooperation, such as self-repair concrete, conductive concrete, heat resistant concrete, plant concrete, radiation resistant concrete and decorative concrete. It is suggested that civil engineering researchers pay attention to the development of these directions and timely introduce some new technologies into the engineering construction field.

18.2 Steel bridges

The construction achievements and technological progress of large-scale steel bridges in China in 2020 are reviewed, these bridges include the longest arch bridge in the world: the 3rd Bridge at Pingnan, the longest road-highspeed-rail suspension bridge in the world: Wufengshan Yangtze Bridge, and the first road-rail strait crossing in China and the longest one in the world: the Pingtan Strait Road-rail Crossing. Great advances in novel and special materials and configurations in steel bridges have been made in the year, including the application of smart iron-based shape memory alloy, the application of stainless steel, the research and application of weathering steel and high-performance steel, the application of aluminium alloy, and the research and application of I-shaped beam formed by butt welding of hot-rolled ribbed flange and steel plate.New advances in orthotropic steel deck (OSD) have been made, including the research and application of hot-casted OSD based on the spherical graphite cast iron, the research of OSD using corrugated core sandwich panel, and the research of high fatigue resistance OSD.

18.3 Composite girder

In conclusion, the shear performance of shear connectors and the bending behaviors of composite girders are still the research hotspots. The introduction of new materials, such as UHPC, high strength steel and other fiber-reinforced concrete, has been received much attention. Simulations and experiments are trying to show more realistic performance under multiple factors, in order to study the effects of complex environments and multi-factor coupling loads. Although there are some researches on durability of materials, an urgent requirement for systematic research on durability of composite bridge structures is needed. Improving the durability of steel-concrete composite bridges is the core technology of the construction of bridge infrastructure. With the natural degradation of material properties, the deterioration of structural original defects and the excitation of damage caused by the service environment, the service performance of steel-concrete composite bridges is studied, and the intelligent perception and diagnosis methods will provide scientific and technological guarantee for the application of composite bridge engineering.

18.4 Bridge seismic resistance

Studying the dynamic response of near-fault and cross-fault bridges has been a hot issue in recent years. How to reduce the seismic damage of bridge piers and effectively realize the self-reset of bridge piers after earthquakes, and how to develop new seismic protection devices to effectively ensure the bridge structure safety and reduction of seismic damage of bridge structures is a research hotspot in the field of bridge seismic resistance, and it is also a research hotspot in the future. With the development of artificial intelligence technology, how to substantively introduce artificial intelligence technology into earthquake engineering is very necessary. Artificial intelligence-based seismic response prediction, seismic wave processing, seismic performance design optimization, and improvement of bridge structural toughness are also studying direction in the future.

18.5 Bridge wind resistance

Recent studies on the bridge wind resistance are mainly paid attention on the wind-induced vibrations, including characteristics of nonlinear flutter, buffeting, vortex-induced vibration, as well as their countermeasures. In future, with the development of super long-span bridges, it is necessary to require continuous innovations of wind-resistant theory, and the effects of nonlinearity and turbulence on the wind-induced vibrations should be consideration in depth. In addition, the use of new scientific and technological means such as artificial intelligence and big data is expected to become an effective way to solve the complex problems of bridge wind engineering.

18.6 Train-bridge coupling vibration research

This article systematically reviews the researches around the world about the wind environment simulation, aerodynamic characteristics test, wind-train-bridge coupled vibration analysis and windproof measures related to the operating safety and comfort of high-speed trains on the railway bridges under crosswinds. Although the above mentioned research has made great progress in recent years, it is still necessary to carry out further research in several aspects as follows with considering the rapid development of railway bridges and the limitation of aerodynamic parameter testing technology: the aerodynamic parameter testing technology of moving trains, the influence of parameter uncertainty and the influence of additional track irregularities on long-span bridges.

18.7 Bridge hydrodynamics

The literature review highlights that the extreme wave loads, wave-current interaction, scour depth prediction, earthquake-induced fluid-structure interaction, and multi-hazard risk assessment in the extreme marine environment are the hot research topics in bridge hydrodynamics of 2020. Future research ought to focus on bridge scour monitoring and countermeasure, misaligned wave and current interaction, fluid-structure interaction under wave and current conditions, multi-hazard prevention and mitigation in coastal environment, especially the development of artificial intelligent technology as tools to guide prevention of hydrodynamic hazards.

18.8 Durability of concrete bridges

According to the above analyses, the authors believe that the research on bridge durability can be carried out from the following aspects in the future: optimization of concrete durability design; development of high-performance and high-durability materials, such as the integrated design of the material (structure) of the concrete bridge and the durability design considering the coupling of multiple factors; high-performance and high-durability bridge construction materials such as modified concrete, UHPC, FRP materials; steel anti-corrosion technology such as steel anti-corrosion agent, self-migrating steel anti-rust technology; damage mechanism related to the durability of concrete bridges; further improvement of the bridge life prediction model.

18.9 Fatigue of steel bridge

The in-depth and systematic researches on this practical engineering problem from different perspectives have been conducted at home and abroad. To clarify the urgent problems and determine the research focuses and development directions in the next stage, the latest research progress in fatigue of steel bridge is summarized, including fatigue failure mechanism and fatigue resistance assessment method, anti-fatigue design and construction technology, environmental factors and their effect mechanism to fatigue resistance, fatigue crack identification, monitoring and detection, fatigue crack treatments and fatigue performance enhancement. The results demonstrate that the fatigue issue is a hot topic to researchers and engineers. The researches on fatigue critical problems in steel bridge has made adequate progress. Based on the studies including anti-fatigue design method, structures with high fatigue resistance, fatigue resistance assessment method, construction technology, fatigue damage monitoring and fatigue micro-crack identification, remaining fatigue life prediction and fatigue performance enhancement. It is the research emphasis and future directions to establish the fatigue resistance technology of steel bridges in life cycle.

18.10 Temperature field and temperature effects of bridge

Bridges' temperature action and effect have attracted more and more attention from researchers. Research on bridge life cycle temperature action considering geographical characteristics, bridge configuration, environment parameters, and reliability is undergoing. Also, temperature-induced bridges static and dynamic response, and their time-varying impact on bridge safety and long-term performance need further research. Besides, more seasonable and effective way of using bridge SHM data to identify bridge temperature effects need to be improved.

18.11 Numerical simulation of bridge structure

With the rapid development of computer technology and the perfection of structural analysis theory, great progress has been made in modeling technology, calculation method and solution method. Structural numerical analysis method has become the favorable way of analyzing various complex problems of bridge structure. It provides a strong tools for the construction and development of bridge industry all over the world. However, due to the complexity of the problem, the current numerical analysis theory and technology still cannot cover all the fields of bridge engineering. Further research works need to be done in the following aspects. 1) The simulation of bridge structure failure process involves a series of problems such as material interaction, cracking, damage propagation and convergence. Therefore, it is necessary to improve the nonlinear model of beam element, including the constitutive relation of material and the nonlinear solution method, so as to enhance the convergence rate of nonlinear analysis algorithm. 2) The numerical model of defection bridge structure under the influence of various environmental factors should be further studied. Various algorithms should be devised for the structural life-cycle mechanical behavior analysis to implement the safety assessment and life prediction of existing structures. With the development of computer technology, parallel computing, cloud computing and other methods have been introduced in the numerical simulation of bridge reaction, which provides the possibility for refined analysis of bridge structure and structural response under multi-field coupling. Therefore, it is also an important work to establish a favorable analysis method of bridge structure based on cloud computing to do response analysis of bridge structure under multi-factor and multi-field coupling. From construction to service stages, the bridge may experience actions of various external factors, and the structure itself has different effects on these factors, such as earthquake, wind, water flow, sea wave, etc. It is necessary to establish a coupling analysis method for the bridge under multi-field action to analyze the results of the interaction between these effects of the structure.

18.12 Box girder and cable-supported bridge analysis theories

It is summarized that the developed new theories about the above two aspects, namely, the box girder and cable supported bridge theories, are promoted by innovation of bridge structural forms, such as the new corrugated steel webs inspired by the forewing of Allomyrina dichotoma, innovative saddle with dumbbell-shaped friction plate. To establish analysis theory aims to help utilize the excellent performances of the new structural forms. With the development of the bridge industrialization, more and more bridge structural forms are expected and will be realized by brilliant and brave bridge engineers worldwide. The analysis theories on the two aspects may be still concerned in the next few years. Thus, expectations are expressed for the mentioned aspects:(1) the analysis theories of box girder with corrugated steel webs need to be systematically summarized, including the calculation methods for axial, bending, shear and torsion static behavior. Moreover, to narrow gap between the scientific research and the practice is also important;(2) to carry out refined experiments for the friction mechanism between saddle and cable for multi-span suspension bridges.(3) benchmark studies for ultimate bearing capacity of cable supported bridges about different numerical models, such as multi-scale FE model, full shell FE model and line element model be carried out by more examples.

18.13 Bridge informatization and intelligent bridge

In recent years, scholars at home and abroad have achieved fruitful research results in the perception, identification, evaluation and prediction of intelligent bridge detection and safety operation and maintenance through informatization and intelligent technology. From the artificial mechanical and electronic perception technology, to the automation equipment based informatization and digital intelligent perception technology development. From the artificial recognition criterion technology, to the data model, data analysis, data mining, deep learning intelligent recognition technology development. From the artificial evaluation expert decision technology, to the data mining (driven), deep learning (intelligent) and quantitative evaluation of the combination of intelligent evaluation and prediction technology development. The informatization, industrialization and intelligent development of bridges are the general trend. The deep integration of artificial intelligence technology into the whole life cycle of bridge planning, design, construction and maintenance will promote the sustainable development of bridges to safety, longevity, green and intelligent.

18.14 Technology of bridge structure test

From the above investigation, it can be seen that measuring and test technology of bridge is one of the hot research areas of bridge structure test, which is mainly reflected in the following aspects: (1) Research on measurement methods based on machine vision; (2) Research on integrated development of sensors; (3) Research on automation and intelligence of detection technology; (4) Further research and development of nondestructive testing technology; (5) Research on test data processing methods based on artificial intelligence technology and big data technology. The authors think that the future development directions of bridge structure test technology are as follows: (1) Intelligent test; (2) Full-field test; (3) Precision manufacturing of the test model; (4) Multi-field coupling complex test; (5) Integrated test measurement and control system.

18.15 Bridge assessment and reinforcement

According to the relevant research on bridge evaluation and reinforcement in 2020 reviewed by the author, combined with the research hotspots in relevant fields in recent years, the above research progress is summarized and prospected as follows: (1) In the aspect of bridge health inspection and monitoring research: the cited literature focuses on reinforcement corrosion and concrete durability. At the same time, the research hotspot of sensor technology and signal preprocessing (front-end computing) is highlighted, especially in the research of fiber grating sensors. It is suggested that targeted research, such as health monitoring methods and equipment suitable for medium and small span bridges, should be carried out to meet the huge demand of health monitoring for medium and small span bridges. (2) In terms of bridge health assessment, in addition to being classified as two research hotspots based on time-varying reliability and based on historical measurement data, structural parameter inversion can be further studied in the context of big data. (3) In the bridge maintenance and reinforcement: work in 2020 in the bending, shear, seismic reinforcement, as well as additional structural system reinforcement and other aspects around the new material research is more. Considering intelligent materials and intelligent monitoring in reinforcement, together with the post-reinforcement evaluation research which has made some progress, may be a new hotspot in the future.(4)In this year, separate summarization of maintenance and reinforcement strategies is added, because the authors believe that the research and the application of strategies and results are of great practical significance both from the perspective of improving the advanced nature of large-scale national infrastructure management and from the perspective of optimizing and saving expenses of owners.

18.16 Prefabricated concrete bridge structures

With the increasing application of prefabricated bridges, researchers have carried out fruitful research on the construction technology, structural measures, and safety of prefabricated assembly structures of prefabricated concrete bridges. With the continuous development of material properties, the ultimate state performance of bridges has been significantly improved. In follow-up research, the following issues should be addressed: how to rationally apply high-performance materials and the prefabricated bridge system to further improve the overall performance of the bridge; how to integrate the replaceability of the prefabricated bridge system into the design and construction of the bridge to achieve anti-seismic performance. The subsequent quick repair is also a hot issue for prefabricated concrete bridges. With the construction of high-speed railways and cross-sea bridges, the serviceability and the durability of bridges are also the important aspects in severe environments. The research on the performance and durability of prefabricated concrete bridges is still slightly insufficient, which may restrict the application scope of prefabricated concrete bridges. The prefabricated bridge structure mainly connects the prefabricated components into a whole through connecting nodes. In the prefabricated bridge structure, the connection method determines the overall performance of the structure. In areas with harsh environments, the connection nodes of prefabricated bridges are prone to deterioration in mechanical performance due to corrosion, radiation, fatigue and other reasons, which affects the overall performance of the bridge. Therefore, it is necessary to study the performance degradation mechanism and characteristics of prefabricated assembly nodes in complex environments, non-destructive testing methods and corresponding reinforcement technologies.

In summary, with the development of bridge science and technology, there are constantly technical problems being researched and overcome, and there are constantly new problems that need to be solved urgently. Due to time constraints, the content introduced in this article will inevitably have deficiencies and omissions. It is hoped that this article can help readers to have a more comprehensive understanding of the latest developments in bridge technology in 2020 to a certain extent, and it will be helpful to all bridge workers in the next research work.

Abbreviations

FRC: Fibre reinforced concrete; UHPC: Ultra-high performance concrete; CFRP: Carbon-fiber-reinforced polymers; RAC: Recycled aggregate concrete; GPC: Geopolymer concrete; UHPGC: Ultra-high performance geopolymer concrete; SMA: Shape memory alloy; SCR: Swing-self-resetting; SGCI: Spherical graphite cast iron; OSD: Orthotropic steel deck; CCSP: Corrugated core sandwich panel; PWHT: Post-weld heat treatment; NiTiNb-SMA: Nickel-titanium-niobium shape memory alloy; ULNR: Unbonded laminated rubber bearings; USRB: Steel mesh rubber bearing; VIV: Vortex-induced vibration; NES: Nonlinear energy sink; CFD: Computational fluid dynamics; LES: Large eddy simulation; EPSD: Evolutionary Power Spectral Density; ASR: Alkali-silica reaction; OSB: Orthotropic steel bridge; SFRC: Steel fiber reinforced concrete; FEA: Finite element analysis; DOFs: Degrees of freedom; Fe-SMA: Fe-based shape memory alloy; FRP: Fiber reinforced polymer; GFRP: Glass fiber reinforced polymer; DOF: Distributed optical fiber; FBG: Intelligent fiber grating; UAV: Unmanned aerial vehicle; OBIA: Object image analysis method; GPR: Ground penetrating radar; SrcNet: Super-resolution fracture network; DRL: Deep reinforcement learning; CRCFTFG: Concrete-filled tubular flange girders; CIG: Corresponding curved I-girder; RTD: Rolling track device; FBG: Fiber Bragg grating; CFST: Concrete-filled steel tube; GRS-IBS: Geosynthetic reinforced soil integrated bridge system; SHM: Structural health monitoring; LBS: Longitudinal boundary stiffness.

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