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REVIEW

# Technological development and engineering applications of novel steel-concrete composite structures

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**ABSTRACT** In view of China's development trend of green building and building industrialization, based on the emerging requirements of the structural engineering community, the development and proposition of novel resource-saving high-performance steel-concrete composite structural systems with adequate safety and durability has become a kernel development trend in structural engineering. This paper provides a state of the art review of China's cutting-edge research and technologies in steel-concrete composite structures in recent years, including the building engineering, the bridge engineering and the special engineering. This paper summarizes the technical principles and applications of the long-span bi-directional composite structures, the long-span composite transfer structures, the comprehensive crack control technique based on uplift-restricted and slip-permitted (URSP) connectors, the steel plate concrete composite (SPCC) strengthen technique, and the innovative composite joints. By improving and revising traditional structure types, the comprehensive superiority of steel-concrete composite structures is well elicited. The research results also indicate that the high-performance steel-concrete composite structures have a promising popularizing prospect in the future.

**KEYWORDS** high-performance composite structure, bi-directional composite, composite transfer, uplift-restricted and slip-permitted connectors, steel plate concrete composite strengthen

## 1 Introduction

The composite structures were invented in the early twentieth century and were first investigated and adopted by developed industrial countries. The systematic research and application of composite construction in China, however, initiated from the 1980s. Based on the design, analysis, and construction of many large-scale complex composite structures and ultra-high-rise composite structures, China has accumulated many innovative technology achievements with independent intellectual properties recently. Many technology difficulties in material science, design methods, construction, and maintenance have been solved, which powerfully guaranteed the successful construction of China's major landmark projects [1]. Compared with reinforced concrete (RC) structures and steel structures, the composite structures have currently become another heated research topic in China. The history of the composite construction in China is summarized briefly as follows:

In terms of the composite components, a series of composite beams were developed first, including the composite beam with laminated slab, the composite beam with prefabricated slab, the channel-shaped composite beam, the composite beam with slab opening, and the composite truss. Many design issues were also investigated systematically, including the interface slip effect, the design method for shear strength, the longitudinal shear design method, and the behavior under bending-shear-torsion loads. The analysis theory and design methods of composite beams were systematically developed and widely adopted in both floor framing systems and overline

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urban bridges. Second, the concrete filled steel tube (CFST) members had significant advantage in performance. Combined with many construction technologies, the CFST members have gained widespread achievements in the construction of many ultra-high-rise buildings and bridges in China. Apart from that, the steel plate-concrete composite (SPCC) member is also an innovative composite member developed recently, and has been popularly adopted in many engineering communities, including the irregular structures, the urban railway bridges, the strengthening of existing RC structures, and high-rise industrial buildings. Because of its significantly improved performance, the SPCC member will play a significant role in the kernel strategic infrastructure constructions of China, such as the large granary and bunker, and the safety shells of nuclear power plants.

In terms of the composite structural systems, the 'connecting' and 'cracking' are the key technical problems circumventing the development of composite construction. In response to the 'connecting' problem, a series of high-performance novel composite joints and hybrid joints have been developed, which directly promoted the construction of the first composite space-launching tower in China. In response to the 'cracking' problem, a systematic crack control technique based on uplift-restricted and slip-permitted (URSP) connector was proposed, which significantly promoted the development of the continuous beam composite bridges, the rigid-frame composite bridges, and the long-span composite bridge deck systems. By the end of 2018, totally 258 ultra-high-rise buildings exceeding 250 m in height will be built in China, with 98.4% of them adopting composite structural system or hybrid structural system. In bridge construction, aside from the traditional composite plate girder and box-girder bridges, many novel composite bridge systems have gained significant development and acknowledgment, including the composite girder bridges with corrugated steel webs, the channel-shaped composite girder bridges, and the rigid-frame composite bridges. Apart from that, many important technological achievements in long-span bridge deck systems, such as the steel-ultra high performance concrete composite bridge deck systems, provide new methodologies to overcome the weakness of traditional pre-stressed bridge deck systems or orthotropic bridge deck systems. These innovations have directly led to the construction of many long-span composite bridges, such as the first composite arch bridge with composite arch and composite girder (the Shenzhen North Station Bridge) and the first suspension bridge with composite bridge deck system (the Yingwuzhou Yangtze River Bridge).

This paper is focused on presenting a state-of-the-art review of five types of steel-concrete composite structures, including (i) the long-span bi-directional composite floors, (ii) the long-span composite transfer structures, (iii) the comprehensive crack control techniques based on URSP connectors, (iv) the SPCC strengthen technique, and (v) the innovative composite joints. For each technology, the layout, the construction procedure, technical advantages, and related experimental or numerical results are illustrated.

## 2 Long-span bi-directional composite floors

The modern building structures are required to be lightweight, long-span, and heavy-load. Widely adopted in floor design, the traditional RC floor is not suitable long-span heavy-load structures because of its unacceptable self-weight, poor seismic resistance, and cracking problem [2]. As shown in Fig. 1, three types of long-span bi-directional composite structures were proposed for improved crack resistance and seismic behavior, including the two-way composite floor, the composite floor with hybrid one-way and two-way steel grillage, and the irregular skew composite floor.

The two-way composite floor is as shown in Fig. 1(a). The floor is composed of side beams, steel grillage, precast slabs, and cast-*in situ* concrete, which were connected together with shear studs. The construction procedure of the floor is as follows. First, fabricate steel beams, weld shear connectors in factory, and install the frame columns, side beams, and steel grillage on site. Second, install the precast slabs above the steel beams and apply temporary support for the slabs. Finally, apply rebar above the precast slabs and pour the concrete. Compared with the traditional RC floor, the two-way composite floor saves the formworks and shortens the construction period. Compared with the traditional one-way composite floor, the structural height is reduced, and the capacity and rigidity is improved. The two-way composite floor has been successfully applied to many long-span infrastructures with significant technical and economic benefits, including the Wuchang Railway Station, the Shenzhen Wanxuan Complex Building, the Qingdao Laigang Building, and the Shenzhen Huarun Center.

The flexural behavior of the two-way composite floor has been investigated by means of experimental and numerical study. The large-scale static loading tests of composite floors were reported [3] and the deformation and load distribution characteristics of specimens were obtained. As shown in Fig. 2, the failure mode of the specimen was the formation of plastic hinge in the steel beam and yield line in the RC floor, the test results showed that the bi-directional steel-concrete composite floor had good ductility and capacity. The flexural stiffness was 2.5 times that of the steel grillage. Based on the test results, the beam-shell hybrid elastoplastic finite element (FE) model was developed to predict the performance of the bi-directional composite floor under concentrated load [4]. In addition, based on the FE analysis, the simplified design method of the bi-directional composite floor was developed. The design formulas of the effective flange width of

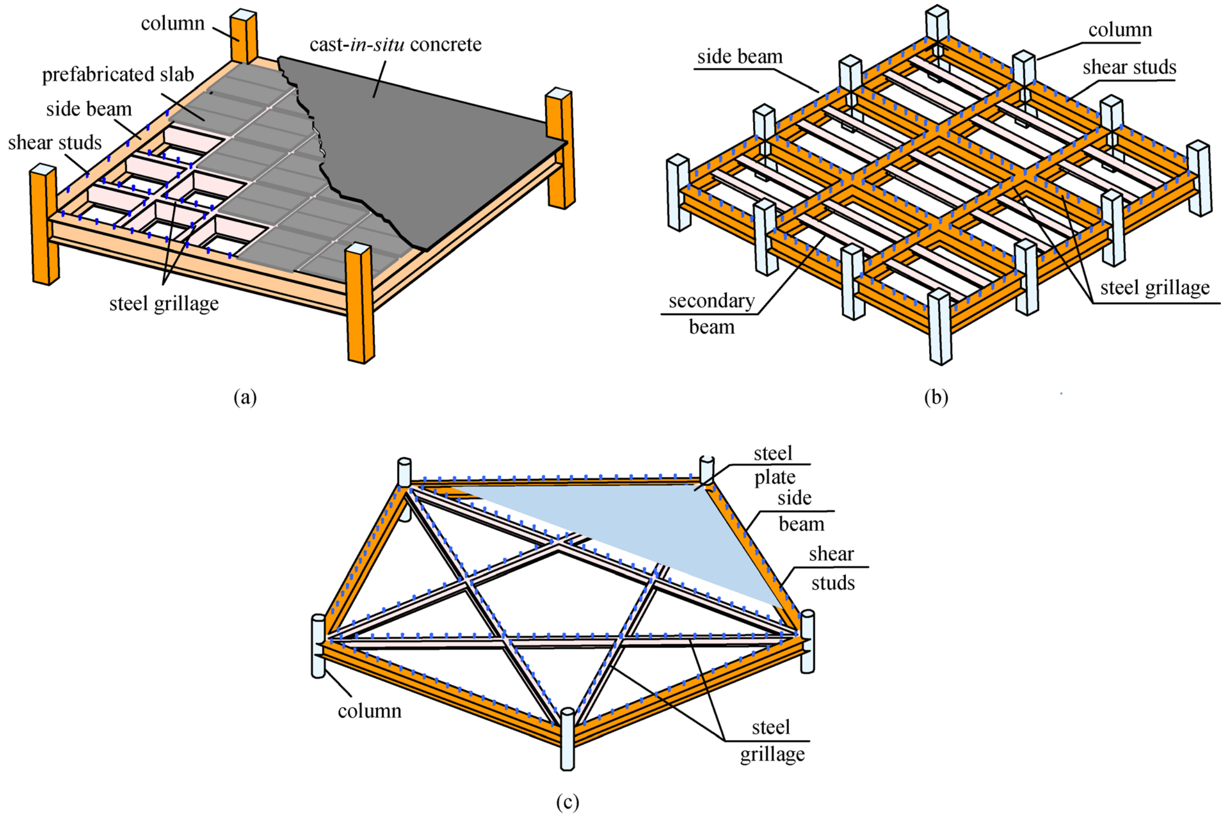



**Fig. 1** Three types of long-span bi-directional composite structures. (a) Two-way composite floor; (b) composite floor with hybrid one-way and two-way steel grillage; (c) irregular skew composite floor

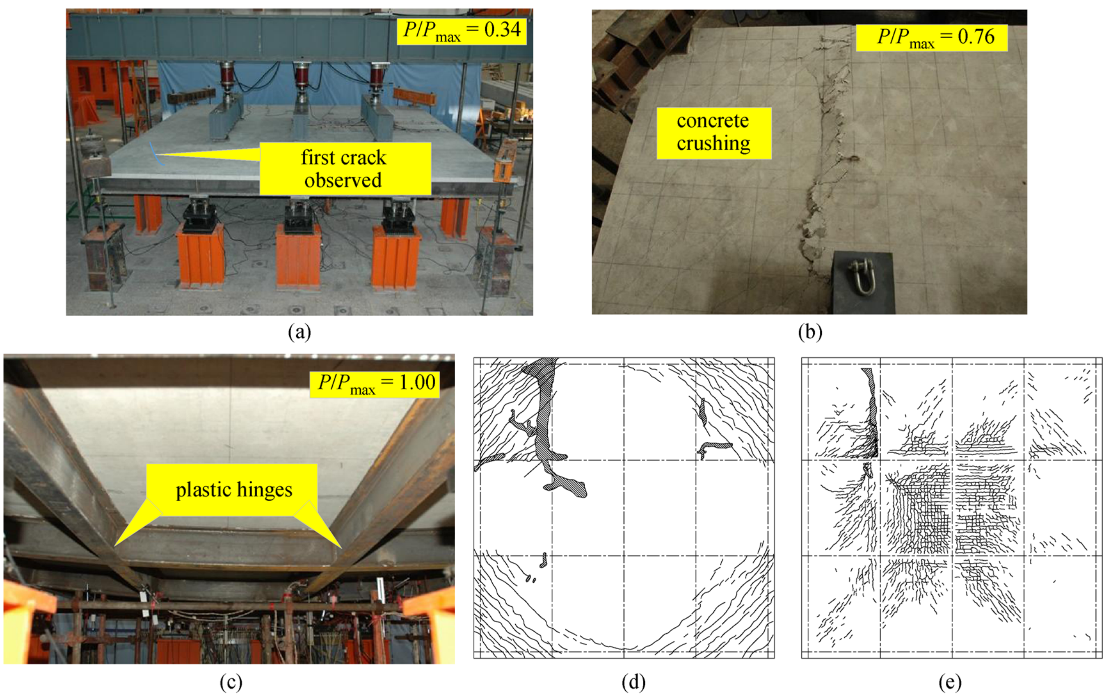



**Fig. 2** Failure modes of long-span bi-directional steel-concrete composite floor [3]. (a) First crack observed; (b) slab crushing and yield line formed; (c) plastic hinges of composite section; (d) damage in top surface; (e) damage in bottom surface

the bi-directional composite floor based on the equivalent strength and the equivalent stiffness were proposed respectively. Eldib et al. [5] developed nonlinear FE model to simulate the static behavior two-way composite floor and one-way composite floor with cold steel straps and showed that the steel straps and studs considerably decreased the slab deflection. Risna and Anima [6] developed nonlinear FE models to investigate the effect of beam spacing and slab opening size on the flexural capacity of the two-way composite floor.

To extend the applicability of the composite floor, the composite floor with hybrid one-way and two-way steel grillage is developed as shown in Fig. 1(b). The floor is composed of side beams, steel grillage, secondary beams, and cast-*in situ* concrete slab. The construction procedure of the floor is as follows. First, fabricate steel beams with welded stud connectors in factory and install the frame columns, side beams, and steel grillage on site. Second, install the secondary beams and formwork on site. Finally, apply rebar and pour the concrete slab. In this floor system, the secondary beams support the concrete formwork during construction and reduce the temporary support. The floor system also reduces amount of beam-column joints, which is beneficial for reducing the construction cost. Compared with the traditional two-way composite floors, the composite floor with hybrid one-way and two-way steel grillage considerably reduces the span of each concrete slab. Therefore, the developed floor system is more suitable for long-span floors.

In addition, with the rapid development of modern architectures, the rapid development of irregular floors has induced complicated stress field and cracking problems in the concrete slab. An irregular skew composite floor is further developed as shown in Fig. 1(c). The floor system is composed of side beams, skew steel beams, steel plates, and cast-*in situ* concrete slabs. The construction procedure of the proposed floor system is as follows. First, fabricate steel beams with welded shear studs in the factory and install the frame columns, side beams, and steel grillage on site. Second, install the steel plate at the bottom of the steel grillage to serve as permanent formwork. Finally, install the rebar and pour the concrete above the steel plate. The pentagon-shaped floor of the Binzhou Convention and Exhibition Center adopts the proposed irregular skew composite floors [7], with a main span of 40.8 m and a column-free floor area of 2019 $m^2$. If the pre-stressed RC beams were used, the beam height would be 3.0 m. If the box steel beams were used, the beam height would be 2.5 m. If the open web steel joist were used, the joist height would be 4.0 m. These design results had unacceptable floor height or self-weight. Finally, by using the proposed irregular skew composite floor, the floor height was reduced to 2.0 m (including the floor thickness of 250 mm). In view of the complex shape of the floor and the sophisticated principal stress direction, the steel plate of 8 mm in thickness was used in to replace traditional positive moment rebar and to control concrete cracking. The steel weight of irregular skew composite floor in this project was only 127.9 kg/$m^2$, which was reduced by 23% compared with the steel box girder scheme. The self-weight of the floor system was reduced by 64% compared with the pre-stressed concrete floor scheme. In summary, the long-span bi-directional composite structure improves the utilization efficiency of steel and concrete, and has the advantages of improved construction feasibility, capacity and rigidity, with a broad application potential in the long-span floor systems.

## 3 Long-span composite transfer structures

As shown in Fig. 3(a), with the increasing requirement for large openings at the ground floor, it is often necessary to provide a horizontal transfer structure, namely a transfer structure [8], on the floor where the structure is converted. The traditional transfer structure mainly used RC transfer beams or steel reinforced concrete (SRC) transfer beams, as shown in Figs. 3(b) and 3(c). These traditional transfer beams had high structural height, induced significant seismic response, and had limited spanning capacity. The RC and SRC transfer beams also had difficulties in construction and crack prevention. The beam-column joint between traditional transfer beams and columns is vulnerable to brittle shear failure under seismic load. In response to the aforementioned problems, the authors developed a new steel-concrete composite transfer structure as shown in Fig. 3(d), which consists of CFST columns and steel-concrete composite transfer beams. The composite transfer structure has significantly reduced structural height and self-weight and enhanced spanning capacity. The proposed composite transfer structure is also convenient in construction.

In high-rise buildings, traditional composite transfer beams are generally subject to heavy vertical load with thin slabs, which could cause local buckling of bottom flanges at the support section. The authors proposed an innovative composite beam section as shown in Fig. 3(d), which could effectively prevent the local buckling failure of the bottom flange. The bottom concrete was removed at mid-span to further reduce its self-weight. The proposed composite transfer beam is particularly suitable for the side beam or thin floor. Recently, the proposed composite transfer structure has been applied to many long-span heavy-load structures, such as the Guangzhou Yufeng Project and Guangzhou Dongpu Fupeng Hotel Project. Compared with the traditional RC transfer structure, the long-span composite transfer structural system can reduce the self-weight of the transfer floor by 60%, thereby significantly reducing the structural height and improving the seismic resistance.

To investigate the mechanical behavior of the composite transfer structures, the large scale test was conducted with

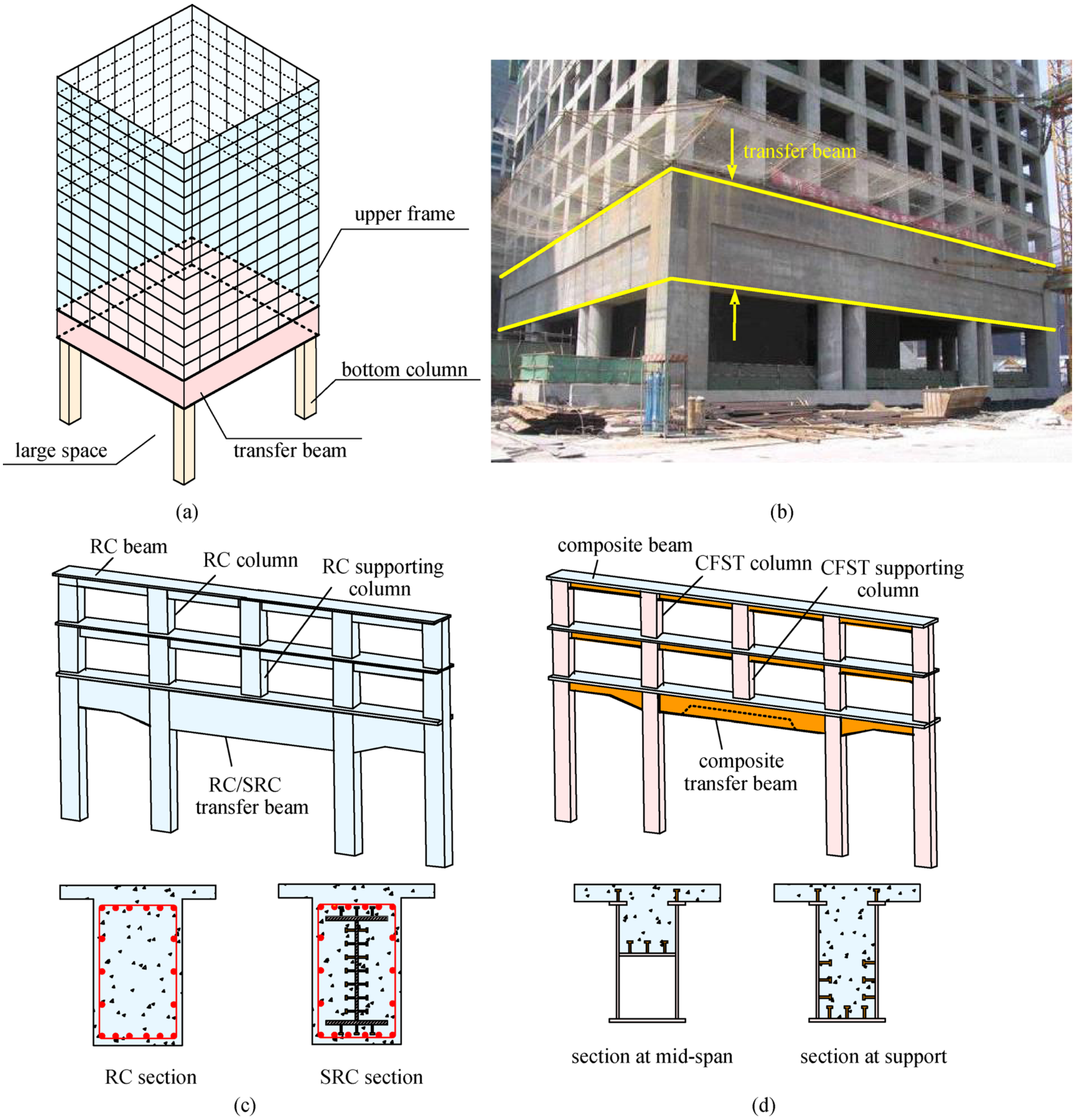



**Fig. 3** Different schemes of transfer beams in practical engineering projects [8]. (a) Transfer beam in high-rise building; (b) traditional RC transfer beam; (c) RC/SRC transfer frame structure; (d) steel-concrete composite transfer frame structure

the vertical load and low-cycle reciprocating horizontal load [8–10]. The test results showed that the composite transfer beam was intact throughout the loading history and the plastic hinge was not observed in the composite transfer beam. To effectively simulate the long-span composite transfer structural system, a multi-scale FE simulation method based on fiber beam-column elements and multi-layer shell elements was developed [8]. Figure 4 shows the comparison of the load-displacement curves between the test and the FE simulation. As shown in Fig. 4, the developed FE model predicted the overall mechanical properties of both the whole frame and each floor with reasonable accuracy. Therefore, an efficient tool for accurate analysis of the seismic performance of the composite transfer structure is established. Based on the experimental and numerical studies, the flexural design method and story drift ratio limit of the composite transfer beam were proposed [9]. In addition, seismic design recommendations were proposed based on test results, including limiting the composite transfer beam stiffness and the beam height, and recommendations for enhanced design of the beam-column joints. In conclusion, with the development of the high-performance structures in the future, the long-span composite transfer structure has broad application prospects.

## 4 URSP connectors for crack control

Shear connectors are used to connect the concrete and steel in composite structures. For certain structural systems, the stability and capacity of composite structures is signifi-

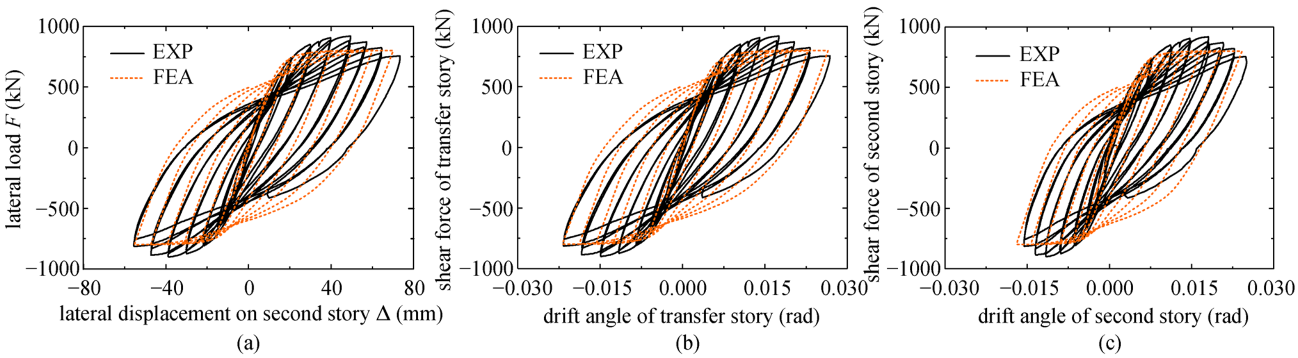



**Fig. 4** Load-displacement hysteretic curves [8]. (a) General behavior; (b) behavior of transfer story; (c) behavior of second story

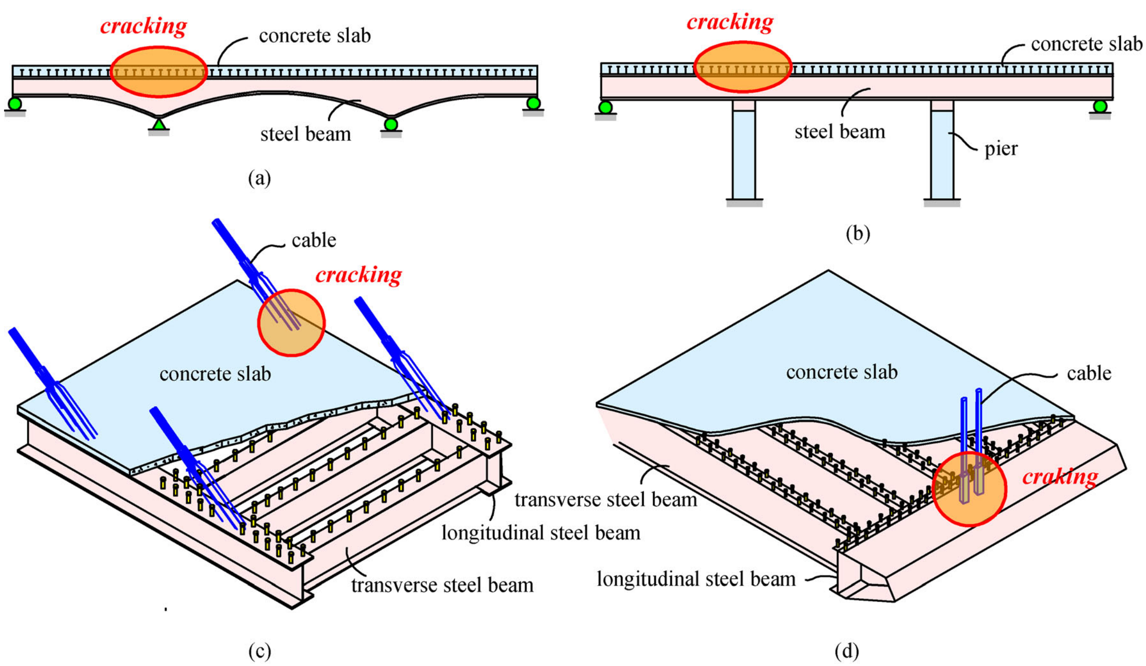



**Fig. 5** Cracking in steel-concrete composite structures. (a) Continuous composite beam bridge; (b) composite rigid frame bridge; (c) composite deck system of cable-stayed bridge; (d) composite deck system of suspension bridge

cantly improved by applying full composite action. As shown in Fig. 5, most large-scale engineering structures are statically indeterminate and the hogging moment and stress concentration widely exist in complex structures. The full composite action in these zones may induce compressive stress in steel plate and tensile stress in concrete. In addition, the composite action also induces shrinkage cracking and reduces the performance and durability of composite structures. Therefore, the concrete crack control has become an important problem in composite structures. Presently, commonly used crack control methods include pre-stressing method, encrypted longitudinal reinforcement method, and construction procedure method [11]. Although these methods alleviate the cracking problem of the composite structures, the problems of complicated details, construction difficulty, and poor long-term performance still exist. In response to these problems, the authors proposed the URSP connector as shown in Fig. 6. Based on special detailed design, the sliding capability of the connector is enabled to a certain extent, which partially released the constraint of the concrete slab in the hogging moment region. It is beneficial for the redistribution of the local tensile stress and the pre-stress introduction efficiency. Meanwhile, the URSP connector resists the vertical separation between steel and concrete.

To achieve the aforementioned properties, three kinds of URSP connectors, namely the URSP-sliding connector [12], the URSP-T connector [13], and the URSP-screw connector [14], were proposed. The URSP-sliding connector is as shown in Fig. 6(b). An elliptical hole is bored at the top flange of the steel beam to control the slip capability. During construction, the stud is placed on the

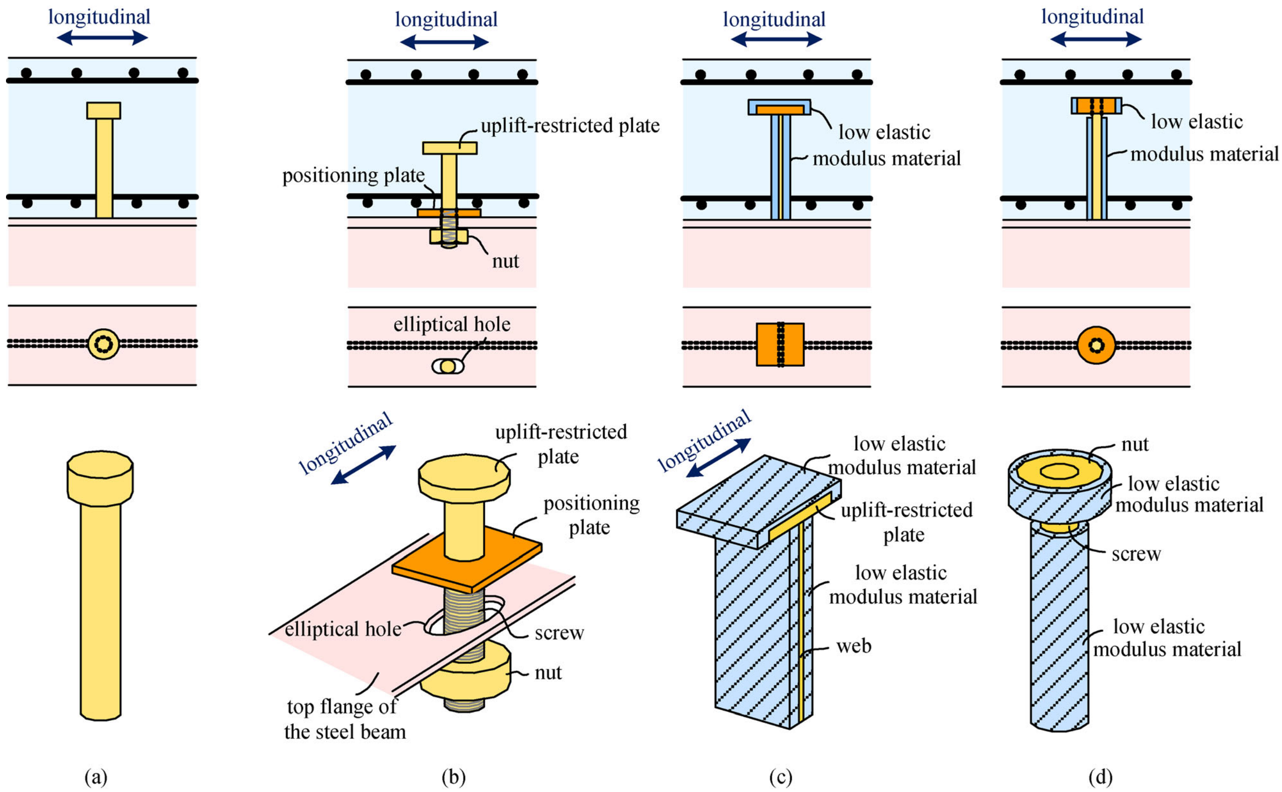



**Fig. 6** Traditional stud connector and three kinds of URSP connector. (a) Traditional stud connector; (b) URSP-sliding connector; (c) URSP-T connector; (d) URSP-screw connector

elliptical hole by the positioning plate. Then the concrete slab is cast and the nut is fixed at the top of the stud. The URSP-T connector is as shown in Fig. 6(c). The connector consists of a conventional T-shaped connector and a low elastic modulus material. T-shaped connectors are welded on the steel beam in the factory. Subsequently, the low elastic modulus material is pasted on the web and top flange of the T-connector to release the shear constraint. Based on the aforementioned connectors, the URSP-screw connector was further developed. As shown in Fig. 6(d), the connector consists of nuts, screws, and low elastic modulus materials. The screw is first welded on the top flange of the steel beam. Then the prefabricated cylindrical low elastic modulus material is installed on the screw. Finally the nut is fixed on the top of the screw. If large interface slip is required, an additional cylindrical low elastic modulus material can be put on the nut. Compared with the previous two types of connectors, the URSP-screw connectors are simple in construction, convenient in installation, reliable in performance, and controllable in slippage, which is beneficial for engineering design.

To verify the crack resistance of the URSP connector in the hogging moment region, a series of experimental study on composite beams was carried out [15,16]. First, two steel truss-concrete composite beams were tested under hogging moment at the scale ratio of 1/5. The CTGB-1 used URSP connectors while the CTGB-2 specimen used traditional stud connectors [16]. The observed crack width is as shown in Fig. 7. Test results showed that CTGB-2 had similar stiffness and flexural capacity as those CTGB-1. Compared with CTGB-1, the CTGB-2 had a significantly higher cracking load and the crack width under the same load was also reduced 50%. In addition, the large scale experimental study on three continuous composite beams was carried out [17,18]. The test results showed that the URSP connector significantly reduced the crack width without affecting the ultimate loading capacity and bending stiffness. As for the mechanical behavior of the URSP-T connector, the shear hysteresis test and pull-out test were carried out [19–22]. The loading device and the failure mode are as shown in Figs. 7(b) and 7(c). Two failure modes of the URSP connector was observed in the pull-out test, namely the yielding of connector web and the punching shear failure of concrete. Through proper design and details, sufficient pull-out capacity of the URSP connector can be guaranteed. Based on the shear hysteresis test, the constitutive model and design method for the URSP connector were proposed as shown in Figs. 7(d)–7(f). The shear force-displacement hysteresis curve of the connector showed significant pinching effect and ductility. The test results showed that the shear sliding displacement of the URSP connector was $1/3t_s$, where $t_s$ denotes the thickness of low-modulus material. Therefore, the design recommendation for choosing $t_s$ is proposed as follows:

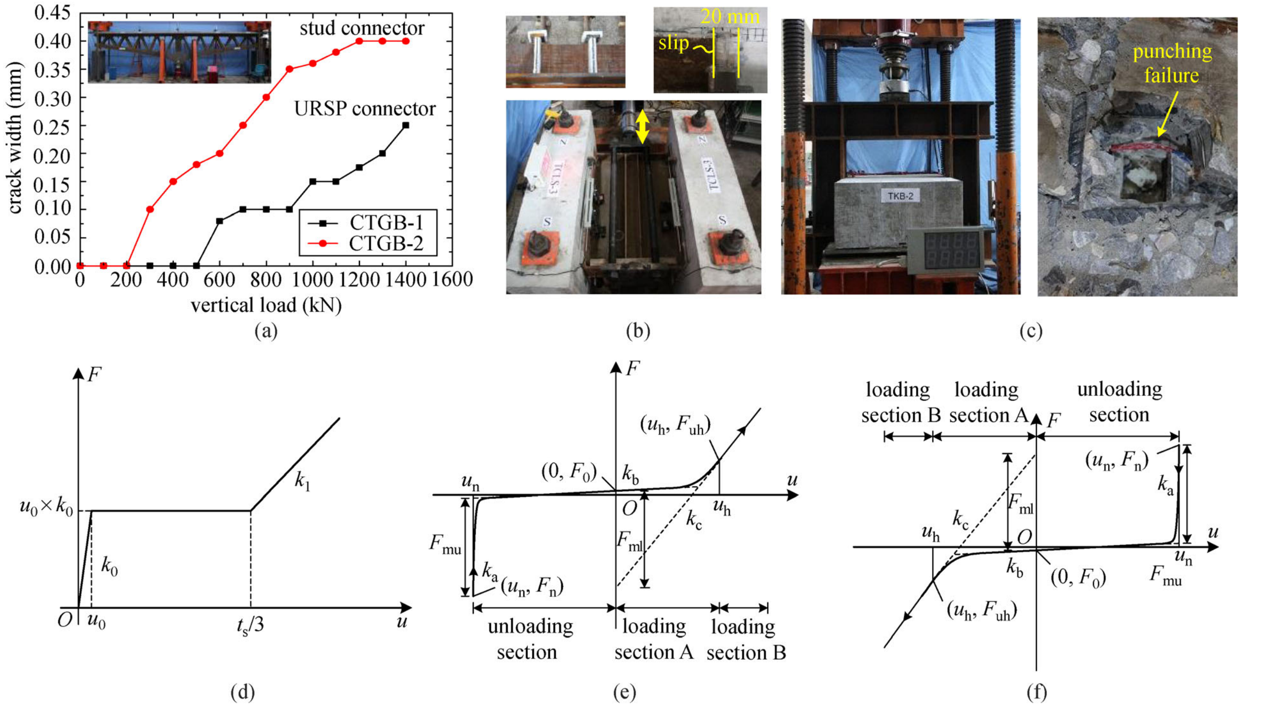



**Fig. 7** Experimental study on shear and pull-out load of URSP connector [19]. (a) Crack width in negative moment test; (b) shear hysteretic test; (c) pull-out test; (d) skeleton curve; (e) reloading curve; (f) unloading curve

(i) conduct FE analysis with nonlinear interface element to calculate the required slip between the steel and concrete under service load; (ii) Set $t_s$ to be more than three times of the required slip. The $t_s$ ranged from 25 mm to 30 mm in some bridge projects.

The URSP connectors have been widely adopted in many projects, achieving significant social and economic benefits. As shown in Fig. 8, the steel consumption was significantly reduced in the Tianjin Haihe River Jizhao Bridge through application of the URSP connector and optimization of the construction process. The maximum tensile stress in concrete was also effectively controlled. On-site test showed sufficient crack resistance which met the design requirements. The National Highway 107 Shenzhen Xingwei-Huangtian U-turn Bridge is a continuous composite bridge with small radius of curvature. The stress distribution on concrete was complicated, and the tensile stress in the bridge deck caused by concrete shrinkage and temperature effect was unacceptable if the traditional connector was adopted. By adopting the URSP connector at piers and bent caps, tensile stress in deck system was effectively redistributed, and the safety and durability of the bridge was successfully ensured.

## 5 Steel plate concrete composite (SPCC) strengthen technique

Because of the significant increase of safety and durability requirement, many existing RC structures cannot meet the increasing requirement of service load and need strengthening or retrofitting. In response to the significant requirement of strengthening existing RC structures, many techniques had emerged, including the enlarged section method, the externally prestressing method, the externally bonded steel plate or fiber reinforced polymer (FRP) method, and the near surface mounted (NSM) FRP method [23]. As reported in the literatures [24,25], in the traditional externally bonded steel plate or FRP method, the interface between the old and new material has to be designed with sufficient tension strength and shear strength. If the interface between the old and new material is designed improperly, the interface peeling failure is the dominant failure mode, and the ultimate capacity of the strengthened system can be even lower than the capacity of the original RC specimen. In response to the significant peeling failure problem in traditional strengthening methods, the authors proposed SPCC technique [26] to combine the steel plate and concrete materials in strengthening. The steel plate shear strengthen technique is termed SPSS in this paper. Figures 9(a) and 9(b) illustrate the strengthen technique of flexural critical and shear critical RC specimens, respectively, and the design details are as shown in Figs. 9(b) and 9(c). In the proposed technique, the strengthen layer is composed of new concrete, embedded rebar, steel plate, and studs. The retrofit process is as follows. First, unload the live load on existing RC specimens and use chiseling method or high-pressure water jet to increase the surface roughness of the RC specimen. Second, bore holes on the side or the soffit

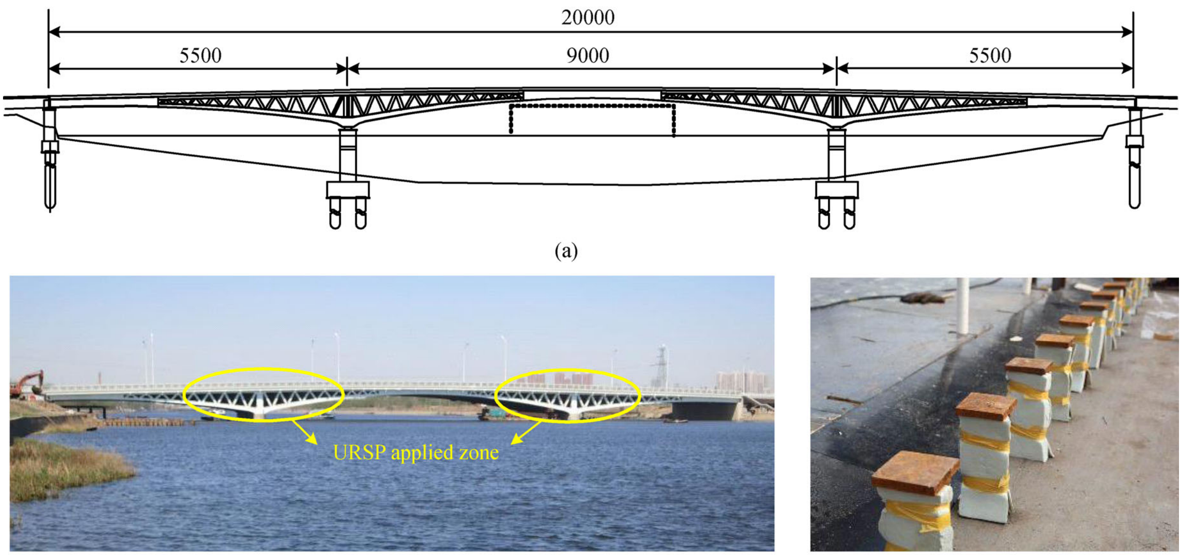



**Fig. 8** Tianjin Haihe River Jizhao Bridge. (a) Elevation (unit: cm); (b) completed bridge; (c) application of URSP on site

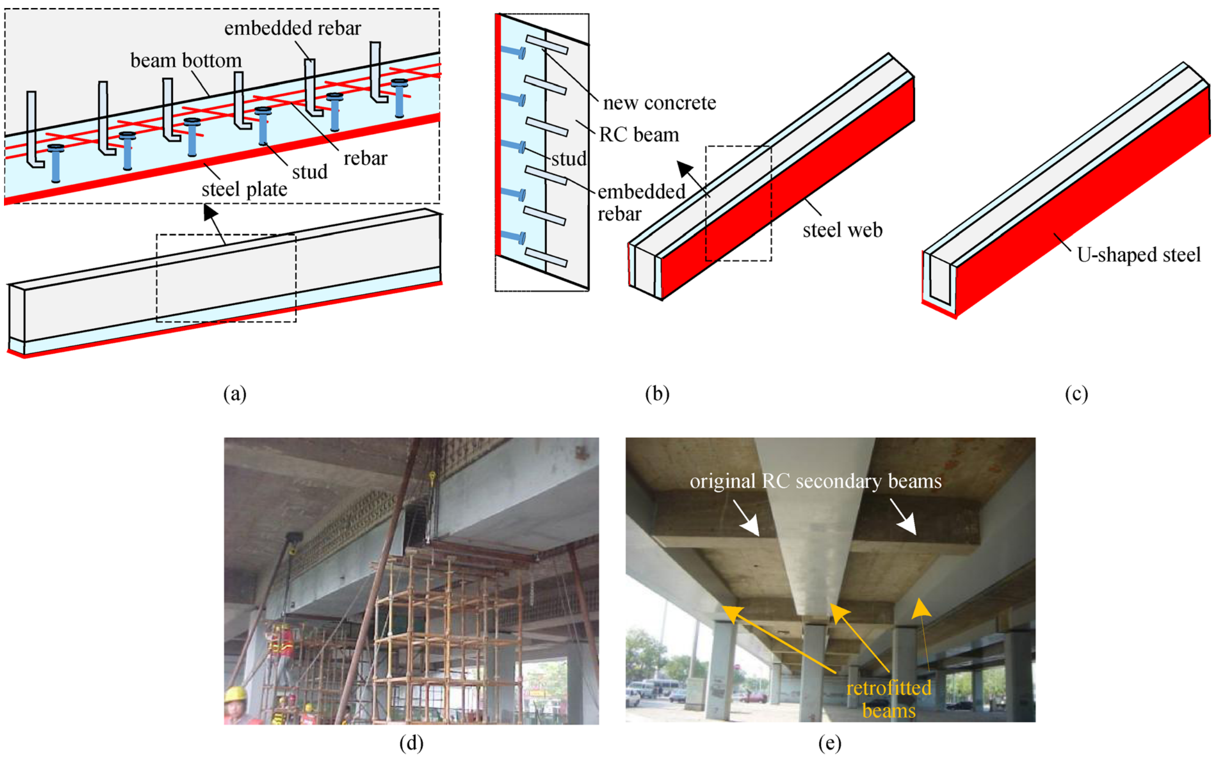



**Fig. 9** Steel plate composite concrete technique and its application in Wanliu bridge [27]. (a) SPCC bending retrofit; (b) SPSS with side retrofit; (c) SPSS with U-shaped retrofit; (d) Wanliu Bridge under retrofit; (e) Wanliu Bridge after retrofit

of the RC specimen and use acetone to clean the holes. The adhesives are used to embed rebar into the holes. Finally, the steel plate with studs are installed and new concrete is poured between the original RC member and the steel plate.

In the proposed SPCC strengthen method, the new concrete is used as connecting material between the original RC specimen and the steel plate. The advantages of the proposed are as follows. First, the SPCC technique can significantly increase the ultimate capacity and stiffness of the specimen. Second, the rebar, concrete, and steel plate are traditional building materials with good mechanical behavior and low cost. Third, the steel plate transfers tensile stress in any direction and solves the tensile cracking problem of concrete in complicated structures, such as the inclined bridge, the skew bridge, and the irregular slab. The steel plate significantly protects the concrete and avoids the corrosion of rebar inside, therefore meeting the service state requirements. Finally, the steel plate serves as formwork for pouring new concrete. Apart from that, the SPCC specimens has significantly improved antiknock ability, anti-permeability, and impact property. For the urban bridges, the proposed technology is especially beneficial for reducing the collision influence of super high vehicles. Recently, the SPCC technique has been adopted in retrofitting many bridges and achieved significant economic benefits, such as Zizhuyuan Bridge, Wanliu Bridge, Fengyi Bridge, Madian Bridge, and Yangqiao Bridge. The retrofit process of Wanliu Bridge is as shown in Figs. 9(d) and 9(e) [28]. In Figs. 9(d) and 9(e), the longitudinal RC beams were retrofitted and the secondary beams was not retrofitted. Apart from that, the SPCC technique has also been used in the Beijing Research Institute of Petroleum Exploration and Development building, where the RC beam was strengthened for demolishing columns.

To investigate the flexural behavior of the SPCC technique, a total of 11 flexural dominated specimens were tested under static loading [26]. The test matrix is illustrated in Table 1. Among the specimens, the RCB-1 and RCB-2 specimens were RC reference beams and other specimens were SPCC beams. The comparison of moment-deflection curves between SPCC beam and the original RC beam are as shown in Fig. 10. The test results showed that when the interface between the old and new concrete was designed with adequate strength, the steel plate and concrete formed a composite section connected by the stud connectors and embedded rebar. The failure mode was the flexural failure mode with compression softening of top concrete and tensile yielding of bottom steel plate and rebar. The SPCC specimen showed significantly enhanced ultimate capacity, stiffness, and ductility compared with the reference RC beam. Under the design service load, the maximum crack width of concrete was limited below the limit of the Chinese code [29]. Based on the test results of flexural critical SPCC specimens, the elaborate FE model considering interface slip was developed and the design recommendations were proposed, including the ultimate capacity, flexural stiffness, interface design method between old and new concrete, and the design method of studs [30].

To investigate the fatigue behavior of SPCC technique, the authors completed a fatigue test program composed of 8 flexural critical SPCC specimens [31]. The test results showed that the fatigue failure mode was the fatigue fracture of the bottom steel plate for each specimen. Contrary to the traditional brittle fatigue failure mode of RC beams, the SPCC specimens had significantly enhanced ductility and showed negligible residual deformation after unloading. The test results showed that the fatigue design method in British code [32] had adequate safety in the fatigue design of flexural critical SPCC beams. To investigate the SPSS technique, the authors conducted a test program composed of 19 shear critical specimens [27]. In the test program, the SPSS beams were compared with reference beams where the concrete was poured in a single batch. The test results showed that when the interface between the old and new concrete was designed as recommended, the failure mode of SPSS beams were the shear compression failure mode, and the SPSS beams reached the same capacity as the reference beams, where the concrete was poured in a single batch. Based on the test results, the two-dimensional and three-dimensional FE models were calibrated and the shear

**Table 1** Test matrix of RC beam and strengthened beam

| group | nomenclature | $a$ (mm) | $t_p$ (mm) | $l_{sp}$ (mm) | $s_r$ (mm) | boundary condition | loading prototype |
|---|---|---|---|---|---|---|---|
| / | RCB-1 | 1500 | / | / | / | four point loading | no preloading |
| / | RCB-2 | 1500 | / | / | / | three point loading | no preloading |
| I | SCCSB-1 | 1500 | 8 | 4780 | 100 | four point loading | no preloading |
| I | SCCSB-2 | 1500 | 8 | 4700 | 100 | four point loading | no preloading |
| II | SCCSB-3 | 2500 | 8 | 4780 | 60/100 | three point loading | preloading and unloading |
| II | SCCSB-4 | 2500 | 8 | 4780 | 60/100 | three point loading | preloading and unloading |
| II | SCCSB-5 | 2500 | 8 | 4780 | 60/100 | three point loading | preloading and unloading |
| I | SCCSB-6 | 1500 | 8 | 4780 | 60/100 | four point loading | no preloading |
| II | SCCSB-7 | 2500 | 8 | 4780 | 75/100 | three point loading | preloading and unloading |
| III | SCCSB-8 | 2500 | 8 | 4700 | 60/100 | three point loading | preloading without unloading |
| III | SCCSB-9 | 2500 | 8 | 4700 | 60/100 | three point loading | preloading without unloading |
| III | SCCSB-10 | 2500 | 8 | 4700 | 60/100 | three point loading | preloading without unloading |

*Note: $a$ denotes the shear span length, $t_p$ denotes the bottom steel plate thickness, $l_{sp}$ denotes the length of the bottom steel plate, $s_r$ denotes the spacing of embedded rebar.

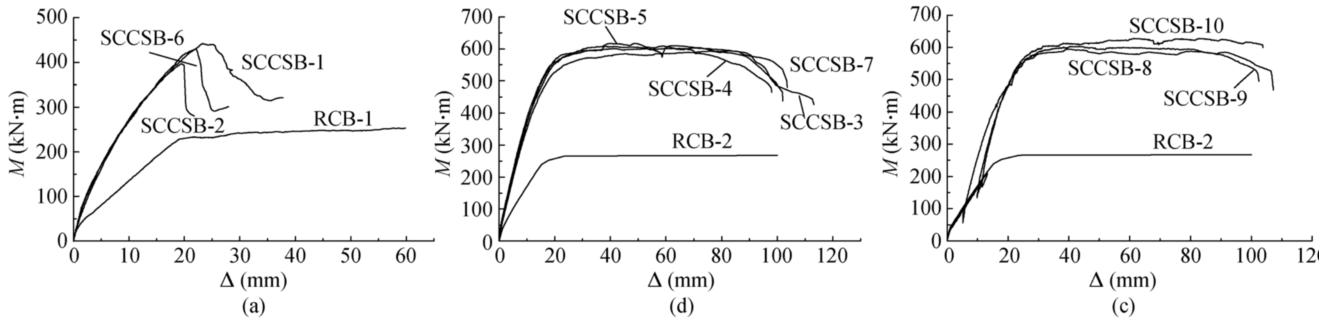



**Fig. 10** Comparison of moment capacity between steel plate bending strengthened beams and reference RC beams [26]. (a) Group I; (b) Group II; (c) Group III

strength design method and interface design method of the SPSS beams were proposed. To further investigate the force transfer mechanism of the interface between the old and new concrete in the proposed SPCC technique, the authors conducted 6 direct shear tests composed of 6 specimens [33]. The test results showed that the interface between the old and new concrete remained intact before reaching the ultimate capacity, and a stable residual shear capacity was observed. Based on the test results, the theoretical interface shear transfer model was proposed and the interface design method of embedded rebar was developed. Furthermore, the maximum area limit for embedded rebar was also proposed to avoid brittle failure of the interface.

## 6 Innovative composite joints

A large number of earthquake damage investigations have reported joint failures caused by improper details as an important reason for structural failure [34]. Therefore, a reliable design of steel-concrete composite joints is the key to achieving a high-performance composite structural system. Composite joints include not only the connection between the composite members, but also the connection between composite members and other structural components. In current research and applications, there is a dearth of systematic design methods and computation models of composite joints. Some traditional joints have complicated details and are difficulty to be applied in engineering practice. The appropriate construction technique of composite joints are still lacking. In view of the insufficient research on the composite joints, the authors proposed a variety of new composite joints and carried out a series of research. Many experimental and theoretical research works were conducted and a series of theories and design methods were established.

The traditional CFST-composite beam joints generally adopts disconnected inner diaphragm as shown in Fig. 11(a). The key feature is that the flanges of the steel beam are welded to the steel tube of column, and the beam moment and shear force are transmitted to the inner diaphragm by complete joint penetration groove weld. Under seismic load, the flanges of steel beam directly tear the steel tube, which easily causes the weld fracture [35]. The ductility of the joints are relatively low because of weld fracture failure. As shown in Fig. 11(b), the composite joints with continuous inner diaphragms significantly avoid the premature weld failure and prevent the tearing failure of CFST column. The authors conducted hysteretic test of totally 24 joints including both disconnected and connected inner diaphragm. The test results showed that the composite joint with continuous inner diaphragms had good ductility and strong energy con-

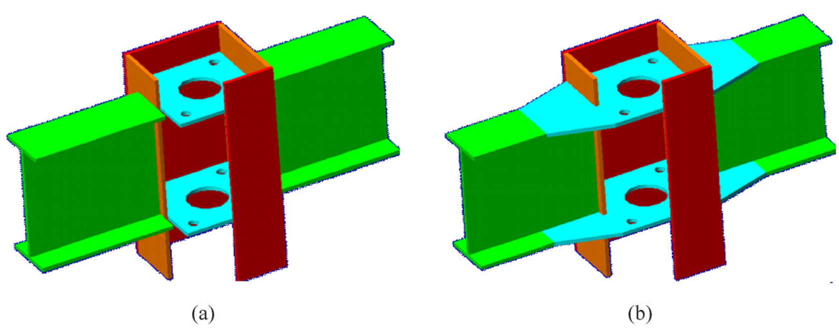



**Fig. 11** CFST column-composite beam joints. (a) Traditional joints with disconnected inner diaphragm; (b) new joints with connected inner diaphragm

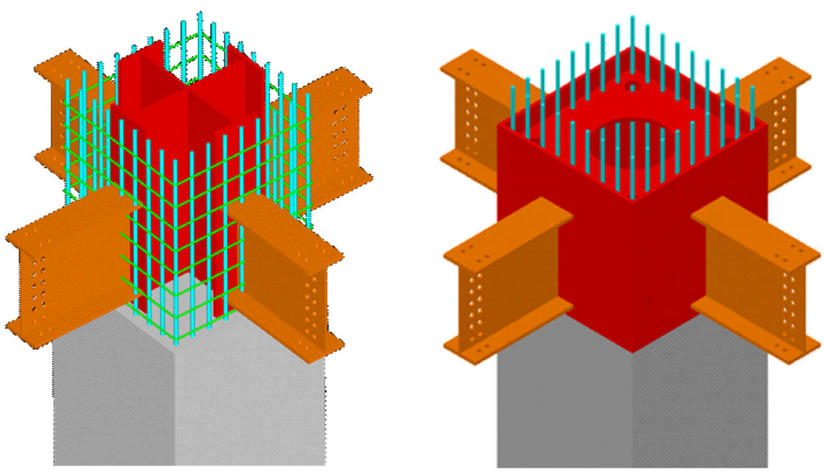
sumption capability. Based on experimental research and numerical simulation, the design method and construction details of the joint were proposed [36–41]. In addition, the existing research on composite joints is mainly focused on planer joint tests. However, the joints in real structures often transfer spatial load in two directions under earthquakes. To study the seismic performance of spatial composite joints with continuous inner diaphragm, experimental study, numerical simulation, and theoretical analysis on seismic performance of the composite joints are conducted. Theoretical model and design method of spatial joints considering the bidirectional seismic forces were also developed [42–48].

The details of the traditional RC column-composite beam joints are as shown in Fig. 12(a). These joints generally have problems such as poor seismic ductility, complicated details, difficulties in construction, and low confinement effect in the core area. In view of these problems of the traditional joints, the authors proposed a new steel sleeve composite joint as shown in Fig. 12(b). The proposed steel sleeve composite joint transfers tension, compression, bending, and shear loads directly through steel sleeve. The steel sleeve composite joint has superior seismic performance. It avoids the exposure of cracks and enhances the confinement effect on the core area. Steel sleeves and steel beams are prefabricated in the factory and installed on site, which is convenient for reducing the construction period. The construction techniques of the steel sleeve composite joints have been widely applied in projects such as the Guangzhou Hejing Building, the Dongguan Youth Activity Center, the Wuchang Railway Station, and the China New Science and Technology Museum. Remarkable social and economic benefits have been achieved.

In addition, the authors completed a multi-directional load test of six CFST-steel beam tilt intersecting joints. Based on the test results, numerical simulation and theoretical analysis were carried out, and the design method and construction recommendations were proposed [49]. In view of the dearth of the design method of SRC column-steel truss composite joints, the seismic performance tests of two large scale joints were carried out. The shear force transfer mechanism and design method considering the confinement effect of the joint core area was established, and the method to control the failure mode was proposed. A precise numerical model suitable for simulating the seismic performance of such joints was developed [50].

## 7 Conclusions

This paper provides a state-of-the-art review of the cutting-edge research and technologies in steel-concrete composite structures in nowadays China, including the long-span bi-directional composite structures, the long-span composite transfer structures, the comprehensive crack control method based on URSP connectors, the SPCC strengthen technique, and the innovative composite joints. Based on the application of the aforementioned technologies, the design of many long-span and heavy load structures have been achieved in China. The key technical problems circumventing the development of composite construction, namely the ‘connecting’ and ‘cracking’ problems are also well solved. The composite construction in China has achieved higher applicability, higher safety, and higher economic and environmental performance. In the future, the application of composite structures will be expanded from the building and bridge engineering to more territories, such as ocean engineering, underground structure construction technology, military defense, and strategic storage [51]. The composite structural systems



(a) (b)

**Fig. 12** Comparison between traditional and innovative RC column-steel beam joints. (a) Traditional concrete column-steel beam joints; (b) steel sleeve composite joints will be improved and the applications of new material will further raise the vitality of the composite construction. The life cycle design theory of composite structures under extreme load conditions will also develop gradually. Therefore, the high-performance steel-concrete composite structures have a promising popularizing prospect in the future.

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