Wenchuan Keku Bridge – A non-traditional CFST truss bridge

Wenchuan Keku Bridge lies in Town Wenchuan, is a very important bridge of Wenchuan to Barkam Expressway. It is a non-traditional concrete filled steel tubular (CFST) truss bridge with overall length 6431m and 4 lanes in two ways. The design speed is 80 km/h and service life is 100 years. It was open to traffic at Dec. 2018, and cost 81.5 million US Dollars.

The Wenchuan-Barkam Expressway is 172 kilometers long. It is a significant transportation link between Chengdu, capital of Sichuan Province, and Barkam, capital of Aba Prefecture. Limited by topography, geology and other conditions, the expressway has to be along the ZaguNaohe River in deep-cutting canyon with a height difference of 500 meters and a bottom width of 50 meters where rivers, roads and houses are distributed. Close to Longmenshan fault zone, the environment is ecologically fragile. Wenchuan Keku Bridge's seismic fortification intensity is up to 8 degree, no prefabricated site, no transport corridor, less concrete raw materials, and only 8 months of effective construction time per year.

Under such construction difficulties, concrete beam bridges have large self-weight, poor seismic resistance, large demand for sand and gravel materials, and inconvenient construction; if steel beam bridges are used, large segments cannot be transported and costly, which is unbearable to owners, and there are no prefabricated sites for construction. Therefore, a non-traditional bridge structure is needed to adapt to the harsh construction conditions, and engineers have proposed a CFST truss bridge.

The main girder trusses of Wenchuan Keku Bridge are composed of CFST chord and web tube, which are connected by steel tube transverse braces. Web tubes and lower chord tubes are connected by intersecting joints, and upper chord tubes are connected by embedded anchoring joints. The sub-structure adopts CFST members and pre-stressed steel box cap beam filled with concrete, which are connected with main girders by various stiffness bearings.

For this bridge, its steel structure doubles as concreting formwork to achieve no extra formwork construction. All the steel structures were manufactured in factories. The main girders and integral piers were erected at one time and the construction of whole span was completed by one day. Only steel structure installation and concrete pouring need to be done at site, 80% of workload was completed in factory, which realize convenient and rapid construction of mountain bridges.

This bridge has outstanding anti-seismic capacity. Engineers optimized the design from three aspects: structure, material and system. Compared with traditional concrete beam bridge, weight of whole bridge is reduced by 46%, and seismic response is reduced by 37%; compared with traditional reinforced concrete piers, CFST piers have better ductility and energy dissipation capacity. Variable stiffness bearings were developed to match stiffness of bearings with stiffness of piers, allowing seismic response reasonably distributed among piers, which reduces the peak value of seismic internal force response of piers greatly.

Wenchuan Keku Bridge has subverted our imagination about traditional highway bridges with its non-traditional structural type. It becomes a benchmark of bridges at complex terrain and mountain areas with high-intensity earthquake by its excellent seismic resistance, convenient and accelerated construction. Wenchuan Keku Bridge promotes the progress and development of bridges in the world. It is definitely worth the Arthur G. Hayden Medal.
Support Material of Wenchuan Keku Bridge

1. Construction condition

Aba Prefecture is located in the western part of Sichuan Province. It is a typical mountainous area in southwestern China. The Wenchuan-Barkam Expressway is 172 kilometers long at South of Aba. Limited by topography, geology and other conditions, the expressway has to be along the ZaguNaohe River in deep-cutting canyon with a height difference of 500 meters and a bottom width of 50 meters where rivers, roads and houses are distributed. Close to Longmenshan fault zone, the seismic intensity is up to 8~9 degree, the earthquake is frequent and ecological environment is extremely fragile.

The proportion of bridges and tunnels on Wenchuan-Barkam Expressway is over 85%, and all bridges are medium and small span structure with overall length of 55 kilometers. The condition is so difficult: high seismic intensity area, no prefabricated site, no transport corridor, little concrete raw materials, fragile environment and very limited effective construction time per year.

2. The limits of traditional bridge structure

Under such construction conditions, if Wenchuan Keku Bridge adopts reinforced concrete structure, the self-weight will make it difficult to meet design requirements for seismic resistance; raw materials such as sand and gravel will consume greatly; meanwhile, lots construction formwork will be assembled and disassembled, which last long time causing construction to be very inconvenient. If steel structure bridge used, large segments are very hard to be transported and assembled at site, besides, its high cost is also unbearable to the owner. Therefore, we need to find a new non-traditional bridge structure to solve these construction problems.

3. Non-traditional bridge structure——Wenchuan Keku Bridge

(1)Concrete filled steel tube material

Concrete filled steel tube is a kind of steel – concrete composite material, because of the hoop effect of steel tube on concrete, compressive strength and anti-deformation capacity of concrete in tube are greatly improved. The lateral support of concrete on steel tube wall avoids tube’s local buckling, increases stability and bearing capacity of steel tube, thus fully exerting the characteristics of steel tube and concrete, and has advantages of light weight, high strength and good ductility.

(2)Bridge structure design

Wenchuan Keku Bridge is a non-traditional CFST truss bridge with single span of 30m or 40m. Figure 1 shows the typical cross section of the bridge. The main truss of upper structure is composed of an upper chord tube of 219 mm, a lower chord tube of 670 mm and a web tube of 402 mm, and filled with concrete. Steel tube transverse braces are set between main trusses to form a CFST main beam with good integrity (as shown in Fig. 2). Web tube and lower chord are connected by intersecting joints, and web tube and upper chord are connected by embedded anchoring joints. The lower chord adopts
pre-tensioned pre-stressed CFST members, and its flexural-tensile bearing capacity is 1.5 times higher than that of non-pre-stressed CFST members.

![Fig.2 CFST main beam](image1)

![Fig.3 Steel-concrete composite deck](image2)

Mounted on the top of main truss is steel-concrete composite bridge deck, including steel bottomslab, welded PBL shear connector and steel mesh, and cast-in-place steel fiber reinforced concrete with total thickness of 15cm (as shown in Fig. 3). The main truss is anchored with the deck to form an integral deck structure with double longitudinal ribs, which bears all loads from the deck.

The main girder is connected with pier by variable stiffness bearing. The pier is CFST frame pier or column pier shown in Fig.4 and Fig.5. The diameter of pier corresponding to span of 30m and 40m is 1.1m and 1.3m respectively. The frame pier spans national road NO.317 underneath, and the top of the pier is set with pre-stressed steel box concrete cap beams. The cap beams and the pier columns are connected by steel slabs with holes, circular welds and vertical anchored stiffening ribs. This kind of piers either avoids occupying the space of national road or meets the need of load transfer. Other piers are column piers with steel tube tied beams at the top.

![Fig.4 CFST column pier](image3)

![Fig.5 CFST frame pier](image4)

Pier bottom and reinforced concrete pile foundation are anchored by steel-concrete composite joint (as shown in Fig. 6). The steel pier at joint is provided with shear holes, inner welded steel slab with holes, outer ring stirrups and reinforced steel tube, and then self-compacting high performance concrete is poured. Multiple anchorage measures can increase safety factor of joints by 2.6 times.

(3) Convenient and Rapid Bridge Construction
Wenchuan Keku Bridge has realized the concept of convenient and rapid construction of mountain bridges. The main truss is transported separately, which solves the problem of large steel members' transportation. CFST piers, pre-stressed steel box concrete cap beams, CFST main girders and steel-concrete composite bridge decks are respectively cast with steel tube, steel box and steel bottom slab as formwork, without additional formwork. All the steel structures were manufactured in factory. Main trusses were quickly assembled when they were transported to site, and more than 80% work can be industrialized. Girders and piers were erected by a special bridge erector at one time, and the construction of a whole span could be completed in one day.

(4) Anti-seismic Characteristics of Structures

The earthquake fortification intensity of Wenchuan Keku Bridge reaches 8 degrees. In order to ensure that the bridge meets the requirements of earthquake resistance, engineers optimized the design from three aspects: structure, material and system.

Firstly, self-weight has a great influence on seismic capacity of bridges. In order to reduce the seismic response of this bridge, the main girder of CFST, steel box concrete cap beam and CFST pier structure are adopted. The cross-section area is small and the weight of structure is light. Compared with concrete T-type beam bridge with the same pier height and beam length, the weight of whole bridge is reduced by 46%, and the seismic response of pier bottom is reduced by 37% under earthquake (seismic peak acceleration is 0.2g for 10% exceeding probability in 50 years), as shown in Figure 8.

Secondly, brittle failure of traditional concrete piers is easy to occur in plastic hinge area under earthquake action. Compared with reinforced concrete piers of the same size, the CFST piers used in this bridge have higher bearing capacity and better ductility. The test results (Fig. 9 and 10) show that the moment-curvature hysteretic curve of CFST columns is fuller and the energy dissipation capacity is stronger than that of reinforced concrete columns.
Finally, the mountain canyons are mostly V-shaped terrain, and the height of piers varies greatly, which leads to the difference of horizontal stiffness of piers. The system length between expansion joints is over 200 meters, if traditional equal stiffness bearing is used in the system, the pier with larger stiffness will be easier damaged during earthquake. The design team developed a kind of variable stiffness bearing and corresponding analysis software. Through the matching design of stiffness between bearings and piers, seismic response is evenly distributed among piers in the system (as shown in Fig. 11). Compared with scheme of equal stiffness bearing system, the piers' peak value of seismic internal force response of Wenchuan Keku Bridge is reduced by 53%.

4. Conclusion

Wenchuan Keku Bridge is an environmental friendly bridge with concept of sustainable development. By structural innovation, the bridge reduces consumption of steel, sand and other resources to the greatest level. Compared with traditional concrete beam bridge, the bridge saves 55% concrete consumption and 19% steel consumption, which greatly saves resources and protects the environment.

This is a non-traditional CFST truss bridge. It perfectly adapts to the construction conditions in China's earthquake mountainous areas, showing excellent seismic resistance and convenient &rapid construction technology. In China, thousands of medium-span bridges will be built in earthquake mountainous areas. This structural type of Wenchuan Keku Bridge has great development prospects. In the near future, this "non-traditional" bridge structure will become more "traditional".