Seismic Technology Development and Innovation for Kilometer-Span Suspension Bridges in High-Seismicity Mountainous Areas of Sichuan

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Abstract

Sichuan′s mountainous regions feature high seismic intensity and require kilometer-span suspension bridges to cross deep canyons. Long-span suspension bridges, with strong spanning capacity and high structural flexibility, are an ideal bridge type for high-seismicity zones. However, increases in main span and pylon height exacerbate longitudinal and transverse seismic issues of pylons. This study adopts innovative structures such as concrete-filled steel tube (CFST) composite pylon columns and corrugated steel web crossbeams to improve the seismic resilience of pylons. Meanwhile, due to the inherent seismic characteristics of long period and large displacement in suspension bridge systems, large seismic displacements occur between the main girder and pylons, bringing high collision risks at girder ends, and seismic responses of pylons are significant. Through collaborative use of energy-dissipative central buckles and girder-end dampers with rational parameters, reasonable stress in the main girder and controllable displacements at girder ends are achieved, and seismic forces on pylons are reduced.

Keywords: high seismic intensity; mountainous area; kilometer-span; suspension bridge; seismic resistance; CFST composite pylon; corrugated steel web composite crossbeam

1 Overview

With the rapid development of the global economy, China is carrying out the world′s largest-scale transportation infrastructure construction, and a number of large bridges crossing rivers and canyons are under planning and construction. Suspension bridges, with their elegant appearance, grand scale, and good seismic performance of flexible systems, have absolute competitive advantages in the design of bridges with a single span of more than 1,000 meters. The western mountainous areas of China are often located in high-intensity zones with complex seismic environments. With the continuous in-depth development of expressways into mountainous areas, the span of suspension bridges and the height of pylons are increasing. Many expressway bridges need to cross the eastern margin of the Qinghai-Tibet Plateau and the Hengduan Mountains, and repeatedly pass through the "Y-shaped" three major active fault zones composed of the Longmenshan Fault Zone, Xianshuihe Fault Zone, and Anninghe Fault Zone in Sichuan. Previous studies on long-span suspension bridges mostly focused on seismic responses, seismic energy dissipation devices between pylons and girders, and traveling wave effects, lacking research on measures to effectively improve seismic performance in high-intensity seismic zones. This paper systematically summarizes the development of seismic technologies for several kilometer-level suspension bridges in high-intensity seismic mountainous areas of Sichuan, conducts research on seismic performance, seismic mitigation measures, and structural system optimization of long-span suspension bridges, and proposes key seismic countermeasures for long-span suspension bridges in high-intensity seismic zones of the Hengduan Mountains, so as to promote the high-quality development of transportation construction in mountainous areas in the future.

2 Representative Kilometer-Level Suspension Bridges in High-Intensity Mountainous Areas of Sichuan

2.1 Luding Dadu River Xingkang Grand Bridge

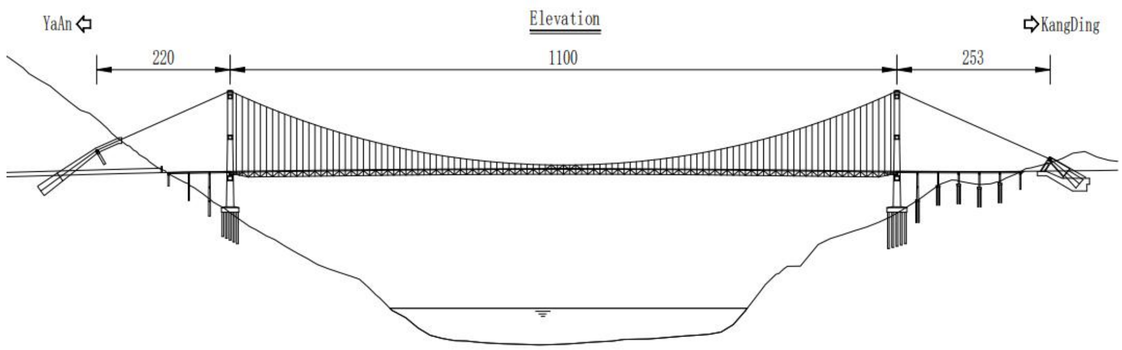


Figure1 Layout of Luding Dadu River Xingkang Grand Bridge (Unit: m)The Luding Dadu River Xingkang Grand Bridge is a major bridge crossing the Dadu River on the Ya′an-Kangding Expressway in Sichuan (Figure 1). The main bridge is a 1,100-m single-span steel truss girder suspension bridge. The pylons adopt reinforced concrete portal frame structures, with a height of 188 m on both banks, and three corrugated steel web composite crossbeams are installed. The basic seismic intensity of the bridge is VIII degree. The design peak acceleration for E1 earthquake (10% exceedance probability in 100 years) is 345 gal, and for E2 earthquake (2% exceedance probability in 50 years) is 490 gal. The bridge was completed and opened to traffic in December 2018.

2.2 Sichuan Kahaluo Jinsha River Bridge

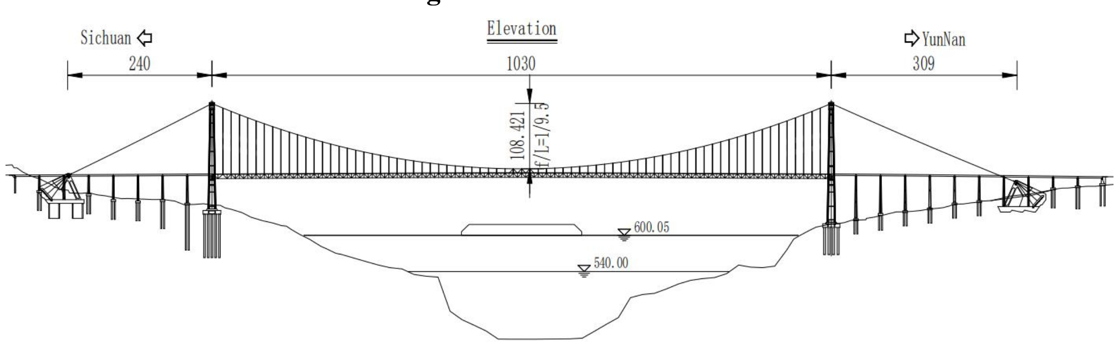


Figure2 Layout of Sichuan Kahaluo Jinsha River Bridge (Unit: m)

The under-construction Sichuan Kahaluo Jinsha River Bridge is a major bridge crossing the Jinsha River on the Yanjiang Expressway (Pingshan Xinshi-Jinyang Section of G4216). The main bridge adopts a 1,030-m single-span steel truss girder suspension bridge. The pylons adopt CFST composite pylons with portal frame structures, and two corrugated steel web composite crossbeams are installed. The pylon height is 175 m on the Sichuan bank and 197 m on the Yunnan bank. The basic seismic intensity is VIII degree. The design peak ground accelerations for E1 (10% exceedance probability in 100 years) and E2 (4% exceedance probability in 100 years) earthquakes are 260 gal and 360 gal, respectively.

2.3 Lugu Lake Grand Bridge on Xichang- Shangri- La Expressway

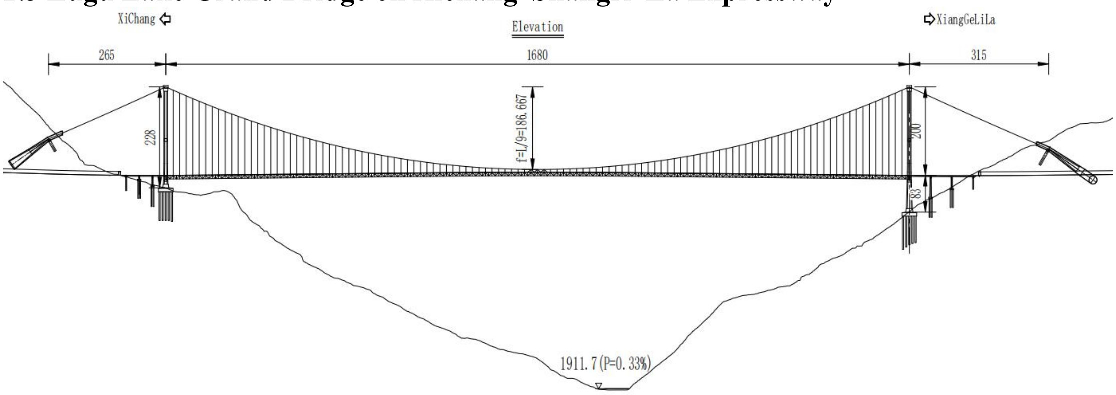


Figure 3 Layout of Lugu Lake Grand Bridge on Xichang- Shangri- La Expressway (Unit: m)

The under- construction Lugu Lake Grand Bridge is located in Yanyuan County, Sichuan Province, spanning the Woluo River on the Xichang- Shangri- La Expressway (G7611). The main bridge is a 1,680- m single- span steel truss girder suspension bridge. To improve wind and seismic resistance, an inward- inclined spatial cable system is adopted. The center distance of the two main cables is 4.3 m at the pylon top and 26.6 m at the mid- span. The main pylons are A- shaped CFST composite pylons, with heights of 228 m and 283 m on both banks, and three steel crossbeams are installed. The basic seismic intensity is VIII degree. The design peak ground accelerations for E1 and E2 earthquakes are 360 gal and 493 gal, respectively.

3 Seismic Response Characteristics of Suspension Bridge Pylons

To study the seismic laws of long- span suspension bridge pylons, the Sichuan Kahaluo Jinsha River Bridge is taken as an example to analyze the structural seismic responses of different main girder types, illustrating the influence of main girder weight on structural seismic responses. Under longitudinal seismic action, the peak bending moments of pylons occur at the middle of the upper pylon column and the pylon base, as shown in Table 1.

Table 1 Comparison of E2 Seismic Moments of Bridge Pylons with Different Main Girder Types

Location	Location	Steel- Concrete Composite Deck System	Orthotropic Steel Deck System	Without Considering Main Girder Mass
Sichuan Bank	Middle of Upper Pylon Column	602729	602602	578534
	Pylon Base	1728109	1726829	1669678
Yunnan Bank	Middle of Upper Pylon Column	1168011	1159338	1148329
	Pylon Base	3356905	3327115	3268047

Calculations show that the seismic response of pylons changes by no more than 3% when using an orthotropic steel deck system (205 kN/m) compared with a steel- concrete composite deck system (306 kN/m). In the extreme case where the main girder mass is completely ignored, the seismic response of pylons on both banks changes by no more than 4%. It can be seen that the seismic response of suspension bridge pylons is insensitive to changes in superstructure loads, and the influence of superstructure types (main girder and deck system) on pylon seismic responses can be neglected; the seismic response of pylons mainly comes from themselves. Similar conclusions can be obtained from transverse calculations, which are not repeated due to space limitations.

The reason why the main girder weight of suspension bridges contributes little to the seismic response of pylons is that it is a flexible structure with a long natural vibration period. The main girder of the vertical suspension system can fully release the seismic force transmitted to the pylons after large displacement under seismic action. In addition, the longitudinal constraint stiffness of the main cables of long-span suspension bridges at the pylon top is much greater than that of the pylons themselves. Most of the limited horizontal force transmitted to the main cables through the non-orienting force effect of the suspenders is transferred to the side cables at the pylon top, so the horizontal force transmitted to the pylons is small, resulting in a small seismic response.

The significance of this study is that in the design of suspension bridges in high-intensity seismic zones, appropriate main girder types can be selected according to on-site topography, geology, construction conditions, manufacturing and transportation conditions, and economic factors, without considering the influence of main girder weight on the seismic performance of pylons. Based on the above conclusions, among several suspension bridges in high-seismic-intensity mountainous areas of Sichuan, except for the Lugu Lake Grand Bridge on the Xichang-Shangri-La Expressway, which adopts a steel truss girder with an orthotropic steel deck due to its large span, the other three kilometer-level suspension bridges (Luding Dadu River Xingkang Grand Bridge, Sichuan Kahaluo Jinsha River Bridge, and Yalong River Grand Bridge on the Xichang-Shangri-La Expressway) all adopt steel truss girders with steel-concrete composite decks suitable for mountain construction and with good durability.

4 Longitudinal Seismic Mitigation Measures Based on Articulated Energy-Dissipative Central Buckle

4.1 Articulated Energy-Dissipative Central Buckle

Long-span suspension bridges are usually equipped with a central buckle at the mid-span to solve the fatigue damage of short suspenders caused by asynchronous cable-girder displacement and improve the antisymmetric torsional stiffness of the structure to enhance the wind stability of the whole bridge. However, how to reasonably select the type of central buckle in high-intensity seismic zones is worthy of study. Traditional rigid and flexible central buckles may not be suitable for suspension bridges in high-intensity seismic zones, as they will cause a significant increase in stress and failure of stiffening girders and central buckle members, reducing the seismic effect. Therefore, based on the design concept of ductile seismic resistance, the Luding Dadu River Xingkang Grand Bridge first uses buckling-restrained steel braces (BRBs) that can yield and dissipate energy as central buckle members, which are connected to cables and girders by hinges at both ends, only bearing axial force without generating bending moment, called an articulated energy-dissipative central buckle. The main feature of BRBs is that they yield without buckling under major earthquakes, and produce large damping after entering the energy-dissipating state to dissipate most of the energy during earthquakes, protecting the main cables and steel truss girders from damage.

Tables 2 and 3 list the internal force calculation results of key pylon sections under several central buckle modes. It can be seen that the internal forces of all key control sections of pylons are improved after installing the central buckle compared with the condition without central buckle, and the improvement range is the largest with the energy-dissipative central buckle mode. Taking the pylon base on the Ya′an side as an example, the improvement degrees of bending moment for rigid, flexible, and energy-dissipative central buckle modes are 9.32%, 8.43%, and 16.95% respectively, and the improvement degrees of shear force are 19.99%, 17.40%, and 20.51% respectively compared with the no-central-buckle mode.

Table 2 Comparison of E2 Seismic Moments at Key Sections of Pylons of Luding Dadu River Xingkang Grand Bridge (kN·m)

Part	Section Location	Without Central Buckle	Rigid Central Buckle	Flexible Central Buckle	Energy-Dissipative Central Buckle

Part	Section Location	Without Central Buckle	Rigid Central Buckle	Flexible Central Buckle	Energy- Dissipative Central Buckle
Ya′an Side	Middle of Upper Pylon Column	1383871	1159451	1247821	1062315
	Pylon Base	3274713	2969433	3015219	2719658
Kangding Side	Middle of Upper Pylon Column	1304562	1063043	1152995	976681
	Pylon Base	3098730	2699087	2934361	2464764

Table 3 Comparison of E2 Seismic Shear Forces at Key Sections of Pylons of Luding Dadu River Xingkang Grand Bridge (kN)

Part	Section Location	Without Central Buckle	Rigid Central Buckle	Flexible Central Buckle	Energy- Dissipative Central Buckle
Ya′an Side	Pylon Top	39342	30643	34304	28037
	Pylon Base	64592	51679	53596	51347
Kangding Side	Pylon Top	37994	28616	32398	25480
	Pylon Base	65766	50324	52611	49757

The stress and displacement responses of the steel truss girder under E2 earthquake are shown in Table 4. It can be seen that the central buckle has a significant effect on limiting longitudinal displacement, but leads to a significant increase in structural seismic stress response. The maximum stress is 162 MPa without central buckle, and the stress of the steel truss girder increases greatly after installing the central buckle, with the peak stress concentrated at the mid- span central buckle. Among the three central buckles, the rigid central buckle has the largest stress, followed by the flexible central buckle, and the energy- dissipative central buckle has the smallest stress, fully demonstrating the great advantage of yield energy dissipation of the BRB central buckle.

Table 4 Comparison of E2 Seismic Analysis Results of Steel Truss Girders

Central Buckle Type	Without Central Buckle	Rigid Central Buckle	Flexible Central Buckle	Energy- Dissipative Central Buckle
Maximum Stress (MPa)	162	734	399	310
Longitudinal Displacement (mm)	2461	898	864	819

The internal forces of rigid and flexible central buckles under E2 earthquake far exceed their bearing capacities, while the energy- dissipative central buckle can be elastic under E1 earthquake through reasonable parameter design. Under E2 earthquake, the axial force exceeds the yield capacity but is less than the ultimate capacity, thus effectively dissipating seismic energy.

By analyzing the calculation results of pylons, steel truss girders, and central buckles, the following conclusions can be drawn: making full use of the abundant stress of the steel truss girder under seismic action without central buckle, and reasonably matching the seismic demand and structural capacity between the steel truss girder and pylons after installing the central buckle can achieve the goals of improving the seismic response of pylons and avoiding yielding of the steel truss girder. Complementing each other′s advantages, the stress potential of each component is effectively utilized, and the cooperative working performance of each component is fully exerted.

4.2 Dampers

Dampers are widely used in bridge seismic mitigation. They do not function under slow loads such as temperature, shrinkage, and creep, but consume vibration energy under impact loads such as vehicle braking force and earthquakes, thus effectively reducing the dynamic response of bridges. Dampers are usually installed between pylons and main girders in long- span suspension bridges. Through parameter analysis of dampers, it is found that the bending moment at the pylon base decreases with the increase of damping coefficient and increases with the increase of velocity exponent, while the damper force shows the opposite rule. By selecting appropriate parameters, dampers can improve the seismic response of suspension bridges without excessively increasing the internal force of the connection structure between pylons and girders, as shown in Table 5. There are many literatures discussing the seismic mitigation effect of dampers on suspension bridges, which will not be repeated here due to space limitations.

4.3 New Seismic Mitigation System of Damper + Energy- Dissipative Central Buckle

From the above analysis, installing an energy- dissipative central buckle at the mid- span of a suspension bridge can effectively reduce the structural seismic response and avoid the failure of the central buckle under high- intensity earthquakes. Meanwhile, installing dampers between pylons and girders can dissipate energy and change the force transmission path of the structure, and selecting appropriate parameters can effectively improve the seismic response of suspension bridges. Both have seismic mitigation effects but are installed at different positions. Therefore, this study proposes a new seismic mitigation system with dampers between pylons and girders and an energy- dissipative central buckle at the mid- span.

To show the characteristics of the new seismic mitigation system using both dampers and energy- dissipative central buckles, the seismic responses under three different seismic mitigation systems are compared: damper only, energy- dissipative central buckle only, and damper + energy- dissipative central buckle. After parameter optimization, the damping coefficient of the viscous damper is 3000, the velocity exponent is 0.3, the yield capacity of the energy- dissipative central buckle is 6000 kN, the ultimate capacity is 9000 kN, the pre- yield stiffness is 550000 kN/m, and the post- yield stiffness ratio is 0.03. Table 5 shows the comparison of seismic responses of the Luding Dadu River Xingkang Grand Bridge under different systems.

Table 5 Comparison of Seismic Responses of Suspension Bridges under Three Seismic Reduction Systems

Structural Part	Seismic Response Component	Damper (1)	Central Buckle (2)	Damper + Central Buckle (3)	(3) − (1)/(1)	(3) − (2)/(2)
Bridge Pylon	Moment at Middle of Upper Pylon Column (kN·m)	1189773	976681	905990	−23.9%	−7.2%
	Moment at Pylon Base (kN·m)	3298680	2464764	2448426	−25.8%	−0.7%
	Shear Force at Pylon Top (kN)	35778	25480	23168	−35.2%	−9.1%
	Shear Force at Pylon Base (kN)	59165	49757	47754	−19.3%	−4.0%
Steel Truss Girder	Maximum Stress (MPa)	126	399	320	154.0%	−19.8%
	Longitudinal Displacement (mm)	976	819	543	−44.4%	−33.7%
Damper	Displacement (mm)	1009	—	515	−49.0%	—
	Force (kN)	3142	—	3336	6.2%	—
Central Buckle	Axial Force under E1 Earthquake (kN)	—	6028	4239	—	−29.7%
	Axial Force under E2 Earthquake (kN)	—	8787	7268	—	−17.3%

It can be seen from the table that System 1 has the largest seismic response, and System 3 has the optimal seismic response. Compared with using dampers only, the seismic response of pylons in System 3 is reduced by about 19.3%–35.2%; compared with using energy-dissipative central buckle only, the seismic response of pylons in System 3 is reduced by about 0.7%–12.2%. System 2 leads to an increase in the stress of the steel truss girder to 399 MPa, exceeding its yield strength, but adding dampers can improve the stress when only installing the central buckle to 320 MPa, indicating that dampers can effectively compensate for the adverse impact of only installing energy-dissipative central buckles on the steel truss girder. All systems can effectively control the longitudinal displacement of the steel truss girder, with System 3 being the best. The internal forces of dampers and central buckles are also optimal in System 3, which can make up for the deficiency of installing only one of them.

Based on the above analysis, the new seismic mitigation system using both dampers and energy-dissipative central buckles is most beneficial to improving the seismic response of suspension bridges and can compensate for the deficiency of installing only one of them. It is an effective longitudinal seismic mitigation measure suitable for suspension bridges in high-intensity seismic zones. The Luding Dadu River Xingkang Grand Bridge first explored and applied such a seismic mitigation system, and then several kilometer-level suspension bridges on the Yanjiang Expressway and Xichang-Shangri-La Expressway adopted such seismic technology.

5 Transverse Seismic Mitigation Measures Based on Corrugated Steel Web Composite Crossbeams

5.1 Overview

Transverse crossbeams of pylons mainly maintain the stability of pylons and increase the transverse overall stiffness of pylons. Under seismic action, they bear large transverse seismic forces and can reduce the internal force of pylon columns. Calculation and analysis of the Luding Dadu River Xingkang Grand Bridge under dead load + seismic conditions show that the bending moments of pylon columns and crossbeams are equivalent, but the shear force of crossbeams is much larger than that of pylon columns, especially the difference between upper and middle pylon columns and crossbeams is very large. The maximum shear force of crossbeams is 40% larger than that of pylon columns (at the pylon base), and the size of lower pylon columns is often much larger than that of crossbeams. Therefore, when the pylons adopt concrete structures, the shear resistance of crossbeams controls the design.

Calculation and analysis show that under sufficient size and reasonable reinforcement, the bending and shear resistance of concrete pylon columns can meet the performance objectives under corresponding seismic fortification standards under different seismic probability levels, while the shear resistance of crossbeams is difficult to meet the requirements. At the same time, whether the selection of crossbeams is reasonable will affect the seismic performance of pylon columns; unreasonable selection will reduce the seismic performance of pylon columns or even fail to meet the requirements. To solve this problem, this study proposes a steel-concrete composite crossbeam type with strong shear resistance.

5.2 Comparison of Crossbeam Schemes

Crossbeams of concrete pylons can adopt three forms: concrete structure, steel structure, and composite structure. For composite crossbeams, the top and bottom plates adopt prestressed concrete structures, and the webs adopt corrugated steel webs. Reasonable sizes are selected for calculation and comparison. As shown in Table 6, when adopting steel crossbeams or composite crossbeams, except for the upper crossbeam, the internal forces of middle and lower crossbeams are greatly reduced compared with concrete crossbeams. The bending moment and shear force of steel box crossbeams are reduced by about 25.9%–29.3% and 33%–34.7% respectively, and those of composite crossbeams are reduced by about 17.5%–27.8% and 19.1%–30.6% respectively.

Table 6 Comparison of E2 Seismic Responses of Crossbeams in Three Schemes

Internal Force	Crossbeam Location	Concrete Crossbeam Scheme	Steel Crossbeam Scheme	Composite Crossbeam Scheme
Moment (kN·m)	Upper Crossbeam	660849	580565	718940
	Middle Crossbeam	1386882	1027410	1143531
	Lower Crossbeam	1613185	1140434	1164901
Shear Force (kN)	Upper Crossbeam	65866	60386	69076
	Middle Crossbeam	111852	74897	90499
	Lower Crossbeam	125962	82250	87435

The calculation results of dead load + transverse seismic moments of pylon columns under the three schemes are shown in Table 7. Both steel crossbeam and composite crossbeam schemes are greatly improved compared with concrete crossbeam schemes. The calculation results of shear force and axial force are similar and will not be repeated due to space limitations.

Table 7 Comparison of E2 Seismic Moments of Pylon Columns in Three Schemes

Part	Concrete Crossbeam Scheme	Steel Crossbeam Scheme	Composite Crossbeam Scheme
At Upper Crossbeam	807078	706953	854996
At Middle Crossbeam	1174576	857440	977232
At Lower Crossbeam	1418420	1077999	1253638
Pylon Base	1985118	1711764	1846258

5.3 Transverse Seismic Mitigation Technology Based on Corrugated Steel Web Composite Crossbeams

From Section 4.2, both steel crossbeams and composite crossbeams can effectively reduce the seismic response of pylons, but the steel- concrete connection structure of steel box crossbeams is complex, and the bending moment at the end of crossbeams is the largest, which violates the design concept that steel- concrete joints should be arranged at places with small bending moments. The connection between corrugated steel web steel- concrete composite crossbeams (Figure 4) and concrete pylon columns is much simpler than that of steel box crossbeams. The connection between top and bottom concrete structures and pylon columns is as simple as that of concrete crossbeams. The connection between corrugated steel webs and pylon concrete can be easily solved by embedding method and PBL shear keys, similar to the connection method of corrugated steel web continuous beams or continuous rigid frame bridges. From the construction perspective, on the one hand, the self- weight is greatly reduced compared with concrete crossbeams; on the other hand, corrugated steel webs can be transported and hoisted in blocks, greatly reducing construction difficulty. Therefore, corrugated steel web composite crossbeams have significant advantages in terms of stress and structure.

Figure 4 Corrugated Steel Web Steel- Concrete Composite Crossbeam

The reasons for the good seismic performance of pylons after adopting corrugated steel web composite crossbeams are mainly: (1) reduced self- weight; (2) reduced stiffness, due to the folding effect of corrugated steel webs, whose axial and bending stiffness can be ignored in calculation, and only the stiffness caused by concrete top and bottom plates is considered.

The Luding Dadu River Xingkang Grand Bridge first explored the application of corrugated steel web composite structures to pylon crossbeams, achieving significant seismic mitigation effects and economic benefits. Subsequently, many mountain suspension bridges adopted this seismic technology, including but not limited to the Sichuan Kahaluo Jinsha River Bridge and Sichuan-Yunnan Jinsha River Bridge on the Yanjiang Expressway, and the Yalong River Grand Bridge on the Xichang-Shangri-La Expressway.

6 Technological Innovation of Concrete-Filled Steel Tube Composite Pylons

6.1 Overview

The seismic innovative technologies described in the previous two sections can solve the seismic technical problems of conventional reinforced concrete pylons (generally not exceeding 200 m) of kilometer-level suspension bridges in high-intensity seismic zones. However, with the further increase of span and pylon height, the contradiction between structural self-weight and seismic response in high-intensity zones leads to the continuous increase of pylon column sections, forming a vicious cycle, which greatly increases the difficulty of seismic design or sharply reduces economy. As demonstrated in Section 2, the seismic response of suspension bridge pylons in high-intensity seismic zones mainly comes from themselves, not from the main girder. Therefore, the design should focus on minimizing the self-weight of pylons to reduce their seismic response, rather than reducing the weight of the superstructure main girder, which is completely different from the design concept of other bridge types.

Suspension bridge pylons commonly adopt steel pylons and reinforced concrete pylons. Obviously, light-weight and high-strength steel pylons are an ideal choice for high-intensity seismic zones in terms of stress, but steel pylons are expensive, have high requirements for construction, transportation, and installation, and require a large amount of later maintenance, so they are not suitable for suspension bridges in mountainous areas.

CFST improves the stability of steel tubes by filling concrete inside, and the concrete inside the tubes can greatly improve its compressive strength and structural ductility based on the confinement effect of steel tubes. Therefore, CFST has been widely used in arch bridges. Suspension bridge pylons are mainly under compression, axial compression members under dead load, and small eccentric compression members under normal service conditions for kilometer-level suspension bridges, with dead load constituting the main part of pylon internal forces. Therefore, CFST structures can be considered to reduce self-weight. On the basis of the aforementioned longitudinal and transverse seismic mitigation measures and collaborative devices, the Sichuan Kahaluo Jinsha River Bridge on the Yanjiang Expressway and the Lugu Lake Grand Bridge on the Xichang-Shangri-La Expressway, based on the seismic characteristics of pylons themselves, further propose a new pylon type of CFST composite structure.

6.2 CFST Composite Pylons with Superposed Columns

CFST superposed columns are widely used in industrial and civil buildings, especially for large and (super) high-rise buildings. They are composed of a central circular CFST column and reinforced concrete superposed outside the steel tube. Superposed column structures can adopt frame, partially frame-supported shear wall, frame-shear wall, shear wall, frame-braced, frame-core tube, and tube-in-tube structure types.

The Sichuan Kahaluo Jinsha River Bridge adopts a box-shaped CFST superposed column form of frame-shear wall (Figure 5). The main structural design ideas are: (1) four CFST columns at the four corners of the section, their outer-packed concrete, and horizontal concrete diaphragms form a frame structure (Figure 6), and then concrete rib slabs are used to connect each CFST column to form a shear wall. (2) The pylon top bears strong vertical loads transmitted by the main cables, in which CFST is the main stress structure and concrete rib slabs are auxiliary stress structures. Under normal service conditions and E1 earthquake conditions, both CFST and reinforced concrete webs participate in stress without cracks or crack widths limited to the allowable range, ensuring the strength and stiffness requirements under normal service conditions. (3) Under E2 rare earthquake conditions, partial separation between shear wall reinforced concrete members and CFST columns is allowed (realized by steel- concrete connectors of different strengths at different parts between them and set horizontal diaphragms) to form an incomplete connection, that is, a weak transverse connecting beam, conforming to the seismic design concept of "strong columns and weak beams". This can reduce the stiffness of pylon columns and extend the natural vibration period of the structure, achieving the goal of reducing the overall seismic effect of pylons.

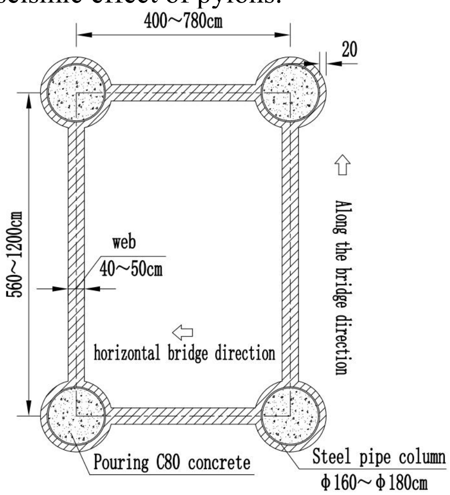


Figure 5 Section 1 of CFST

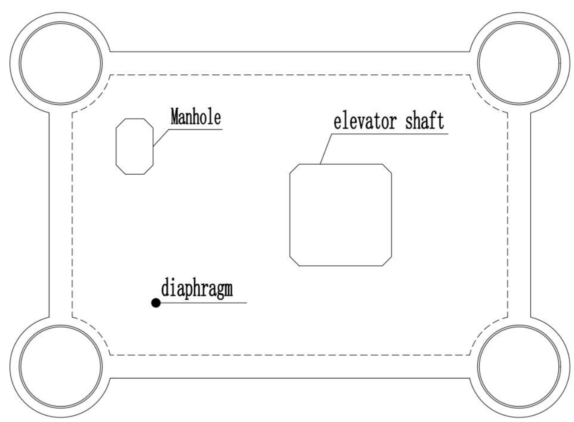
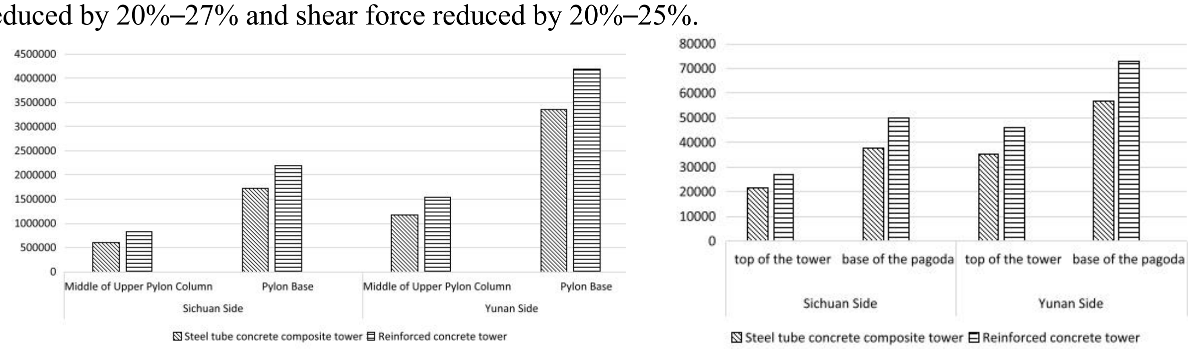


Figure 6 Section 2 of CFST

A comparison between CFST superposed column composite pylons and reinforced concrete pylons is carried out for this bridge. The comparison of calculation results of bending moments and shear forces at each control section under seismic action is shown in Figure 7, where the peak bending moments occur at the middle of the upper pylon column and the pylon base, and the peak shear forces occur at the pylon top and pylon base. Compared with reinforced concrete pylons, CFST composite pylons reduce self- weight by more than 30%, so the seismic response can be greatly improved, with bending moment reduced by 20%–27% and shear force reduced by 20%–25%.



(a) Comparison of E2 Seismic Moments (kN·m) (b) Comparison of E2 Seismic Shear Forces (kN)

Figure 7 Calculation Results of Seismic Responses at Key Sections of Bridge Pylons for Two Schemes

The significant reduction in seismic response naturally leads to material savings. Compared with concrete pylons, the CFST superposed column composite pylons of this bridge can save 8,130 m^3 of concrete, 14,119 m^3 of foundation concrete, increase steel (including reinforcement) by 1,331 tons, and finally save 13.3% of the total cost of pylons (including foundations).

6.3 Steel Tube/Steel Box- Concrete Composite Structure Pylons

Although the pylon type described in Section 5.2 further improves the seismic performance compared with reinforced concrete pylons, because CFST is the main stress structure and thin rib concrete is the auxiliary stress structure, calculations show that it is only suitable for kilometer- level suspension bridges with moderate spans and pylon heights. The Sichuan Kahaluo Jinsha River Bridge has a span of 1,030 m and a steel tube diameter of 1.8 m, exceeding the limit of 1.5 m specified in the current highway CFST arch bridge code. The under- construction Lugu Lake Grand Bridge on the Xichang- Shangri- La Expressway has a span of 1,680 m and a pylon height of nearly 300 m, with seismic intensity ranking first among mountain suspension bridges, posing a great challenge to the bridge′s seismic resistance. If the aforementioned CFST superposed column composite pylons are adopted, a steel tube diameter of 1.8 m is far from meeting the requirements. However, the influence of confinement effect and concrete debonding/voiding of ultra- large diameter CFST on mechanical performance lacks in- depth theoretical research and practical experience, and there will be great safety risks when applied to this bridge. Therefore, on the basis of CFST superposed column composite pylons, this project further creatively proposes a new pylon type of steel tube/steel box- concrete composite structure.

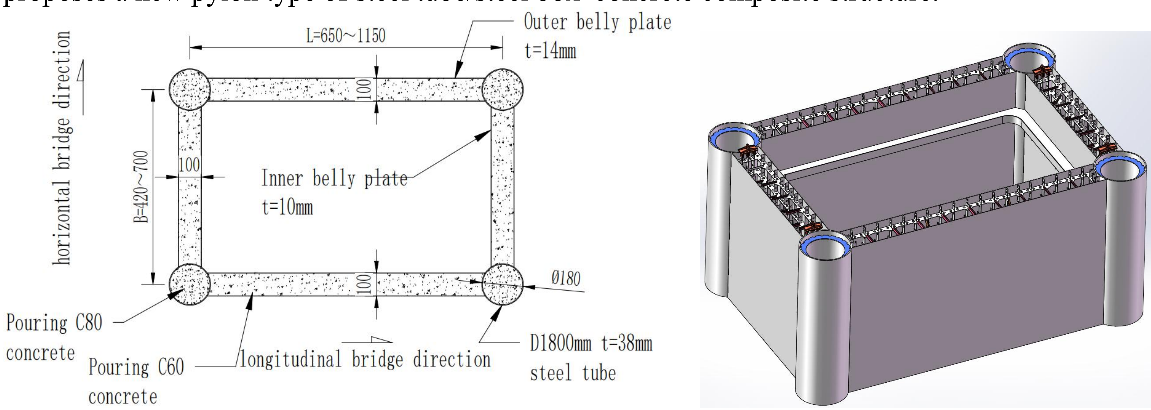


Figure 8 Steel Tube/Steel Box- Concrete Composite Structure Pylon

As shown in Figure 8, the pylon column of this type adopts a single- box single- cell box section, composed of CFST at the four corners of the section and steel box- concrete webs between them. The steel tube diameter is 1.8 m, filled with C80 high- strength concrete, the web thickness is 1 m, filled with C60 concrete, and shear studs are arranged inside the tubes to prevent concrete debonding and effectively strengthen the steel- concrete composite stress between them, ensuring that the stress meets the plane- section assumption. The pylon wall steel box structure is composed of inner and outer steel wall plates, vertical and horizontal stiffeners, vertical and horizontal angle steels, and studs, which can effectively resist the fluid pressure during concrete pouring and ensure the cooperative working mechanism between steel and concrete. At the same time, circumferential stiffeners are installed in each segment to facilitate construction positioning, strengthen the connection between CFST and steel box- concrete, and improve the torsion and distortion resistance of pylon columns. The bearing capacity and seismic resilience of the composite pylon of this structural form are further improved.

In terms of stress, the steel tube/steel box- concrete composite structure pylon is a new type of pylon that emerges by making full use of the respective advantages of steel and concrete structures. Both steel tubes and steel box structures form a confinement or restraint effect on the internal filled concrete, providing strong mutual restraint between steel and concrete, which can greatly improve bearing capacity and seismic resilience. At the same time, it effectively realizes the factory and assembly manufacturing of pylon construction, improving construction efficiency.

Table 8 Calculation Comparison of Bridge Pylon Schemes

Item	Dead Load at Pylon Top (kN)	Self-Weight of Pylon Body (kN)	Axial Force at Pylon Base (kN)	Moment at Pylon Base (kN·m)	Pile Foundation (Pcs)
Reinforced Concrete Pylon	496876	965817	885022	5854116	72
Steel Tube/Steel Box-Concrete Composite Pylon	—	504402	577623	2999035	50

Table 8 shows the main calculation results of steel tube/steel box-concrete composite pylons and reinforced concrete pylons. Compared with reinforced concrete pylons, the new composite structure pylons save 55% of concrete volume and 28% of pylon cost.

The Lugu Lake Grand Bridge started construction on March 1, 2023, and the pylons are about to be capped.

7 Conclusions

Aiming at the characteristics of large spans, large pylon seismic responses, and the increasing demand for seismic performance improvement of suspension bridges in western high-intensity seismic mountainous areas, research on pylon energy dissipation and seismic mitigation measures and new pylon structures has been carried out. The law that the seismic force of pylons mainly comes from themselves is discovered for the first time, which is of great significance to guide the design of suspension bridges in high-intensity seismic zones. The longitudinal seismic mitigation technology based on articulated energy-dissipative central buckle + dampers and the transverse seismic mitigation technology based on corrugated steel web composite crossbeams are proposed for the first time. A new type of light-weight and high-strength CFST composite pylon is creatively proposed, combining the advantages of reinforced concrete pylons and steel structure pylons. The above seismic technologies can provide reference for the seismic design of similar suspension bridges.

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