Key Seismic Design Technologies for the Yalong River Special Bridge on the Xixiang Expressway

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Abstract

The Yalong River Special Bridge on the Xichang–Shangri-La Expressway is a steel truss suspension bridge with a main span of 1200 m. Its pylons are of reinforced concrete and located in a high-intensity seismic region in Sichuan Province. The peak ground accelerations (PGA) corresponding to 10% and 5% exceedance probabilities in 100 years are 410 cm/s^2 and 520 cm/s^2, respectively. To enhance the seismic performance of the bridge, the force distribution mechanism of a main-cable energy-dissipation central buckle and girder-end eddy current dampers was investigated. The results indicate that the combined use of the energy-dissipation central buckle and eddy current dampers can effectively reduce the seismic forces on the pylons and the longitudinal displacements at the girder ends. To improve the transverse seismic behavior of the pylons with ultra-high lower columns, the seismic effect of energy-dissipation hollow steel braces installed at critical joints was studied. It is concluded that installing two pairs of splayed steel braces between the lower pylon columns and the lower crossbeam, and between the lower pylon columns and the pile cap tie beam, yields the optimal seismic performance.

Keywords: *Yalong River Special Bridge; seismic design; energy-dissipation central buckle; eddy current damper*

1. Introduction

With the continuous expansion of transportation infrastructure into mountainous areas in China, long-span suspension bridges have become the preferred structural form for mountainous expressway projects in Sichuan due to their superior spanning capacity to cross deep canyons and complex terrains. Although suspension bridges feature reasonable mechanical behavior and strong spanning ability, they also exhibit high flexibility, low damping ratio, and long natural vibration periods. As the key load-bearing component of long-span suspension bridges, ultra-high concrete pylons are characterized by large self-weight, uneven stiffness distribution, and insufficient lateral resistance. In addition, critical regions such as pylon-girder joints and pylon-foundation connections are subjected to complicated internal forces and tend to become seismic weak points. Therefore, optimizing the seismic system and improving the seismic performance of key components have become the core issues in the seismic design of ultra-high concrete pylons.

2. Project Overview

The Yalong River Special Bridge is a key project of the Xichang–Shangri-La Expressway (Sichuan Section), G7611. It is a single-span steel truss suspension bridge with a main span of 1200 m. The rise-span ratio of the mid-span is 1/9, the transverse center-to-center distance of the main cables is 28.7 m, and the longitudinal spacing of hangers is 13.5 m. The stiffening steel truss adopts a Warren configuration with vertical members, and the truss depth is 7 m. Restricted by transportation conditions, reinforced concrete pylons are adopted. The pylons are portal frames composed of pylon columns and crossbeams, with a height of 231.2 m on both banks, and the lower pylon is 72.3 m. The pylon columns are box-shaped reinforced concrete structures, and the crossbeams are designed as prestressed concrete slabs with corrugated steel webs.

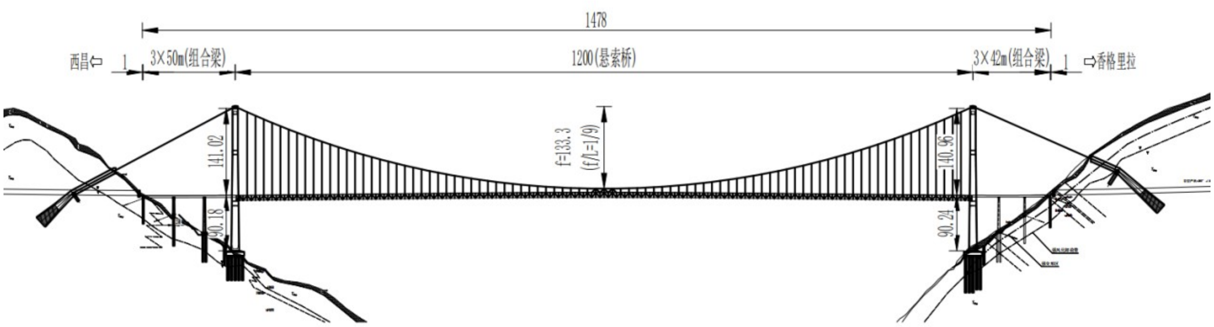

Figure 1 Layout of the Yalong River Super-large Bridge

The bridge is located in a region with complex wind and seismic environments. The basic seismic intensity is Grade VIII, and the PGA under the E2 seismic level reaches 520 cm/s², which is the highest among kilometer-scale bridges in China. The ultra-high pylon columns and extremely high seismic intensity pose severe challenges to the seismic design of the bridge.

3. Longitudinal Seismic System Design

For the longitudinal seismic design of long-span suspension bridges, previous engineering practices have demonstrated that girder-end dampers and central buckles can effectively reduce the displacements of pylons and girder ends as well as the longitudinal seismic responses of pylons under earthquakes.

3.1 Energy-Dissipation Central Buckle

Traditional flexible central buckles only coordinate the relative displacement between the girder and pylons under unidirectional tension during earthquakes. Rigid central buckles may induce large secondary stresses under strong earthquakes and are prone to buckling in compression zones. The Yalong River Special Bridge adopts an articulated energy-dissipation central buckle. Its two ends are hinged to transfer axial forces instead of bending moments, thus avoiding secondary stresses caused by rigid connections. Moreover, the central buckle is made of buckling-restrained brace (BRB) material, which dissipates energy under both tension and compression, further reducing the seismic responses of pylons and the displacements at girder ends.

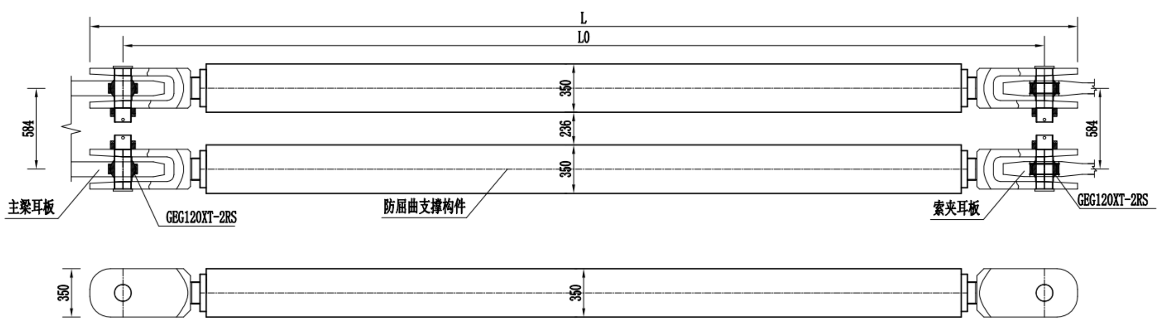

Figure 2 Articulated buckling-restrained steel brace

Buckling-restrained braces are special concentric braces that integrate the functions of conventional braces and metal-yielding energy dissipators. They have been increasingly studied and applied in seismic design worldwide, especially in Japan and the United States. A BRB consists of a core steel member, an external buckling restraining unit, and an unbonded material layer between them. Under seismic axial forces, the core yields in tension and compression to dissipate energy, while the external restraining tube and infilled concrete or mortar prevent the core from buckling.

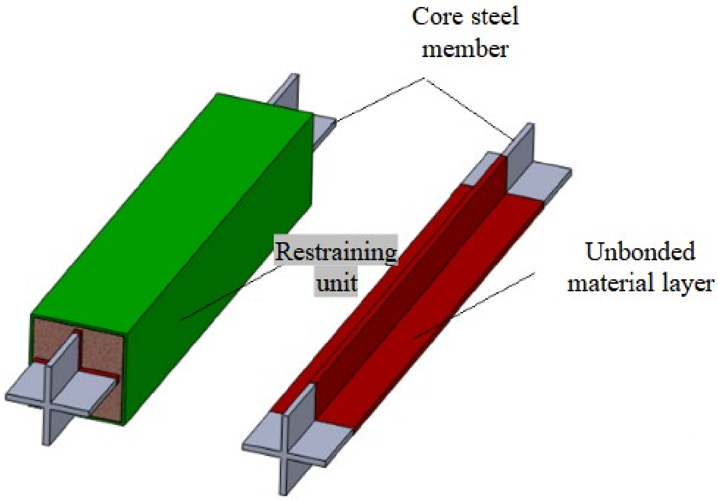

Figure 3 Structure of the buckling-restrained steel brace

3.2 Girder-End Eddy Current Dampers

In the seismic and vibration mitigation system of bridges, dampers are the core energy-dissipation components, and their performance is directly related to the safety and stability of bridges under loads such as earthquakes and strong winds. For nonlinear dampers used in bridge structural vibration reduction, the damping force F has a nonlinear relationship with the motion velocity:

$$F = C v^{\alpha}.$$

Where:

F = damping force

v = relative velocity

C = damping coefficient

α = velocity exponent

Although traditional hydraulic dampers have been widely used, they show obvious limitations under high-intensity earthquakes and extreme temperature differences in mountainous areas of Sichuan. Eddy current dampers have become the preferred solution for long-span suspension bridges in mountainous regions due to the following advantages:

1. Superior durability: Hydraulic dampers are prone to oil leakage and may fail within 3–5 years. Eddy current dampers are all-metal structures free of oil leakage, with a service life matching the bridge design life and requiring no maintenance.

2. Strong environmental adaptability: The performance of hydraulic oil is sensitive to temperature and corrosion, whereas eddy current dampers based on electromagnetic induction exhibit stable performance.

3. High energy-dissipation efficiency: Hydraulic dampers have a delayed response to small-amplitude vibrations, while eddy current dampers are highly sensitive and dissipate energy efficiently.

3.3 Parametric Analysis of the Longitudinal Seismic System

(1) Parametric Analysis of Longitudinal Dampers

Two longitudinal dampers are installed at the girder supports of each pylon. The effects of the velocity exponent α and damping coefficient C on the seismic responses were analyzed without considering the central buckle. The velocity exponent α was set to 0.2, 0.3, and 0.35, and the damping coefficient C was set to 3000, 4000, 4500, 5000, 8000, and 10000 $kN\cdot(s/m)^{\alpha}$. Three seismic waves at the E2 level specified in the seismic safety evaluation report were used for time-history analysis, and the results were taken as envelope values. The ground motion was applied in the longitudinal and vertical directions simultaneously.

The results show that the relative displacement between the pylon and girder decreases significantly with increasing damping coefficient C and is insensitive to the velocity exponent α. The bending moment at the pylon base decreases with increasing damping coefficient and slightly increases with increasing velocity exponent.

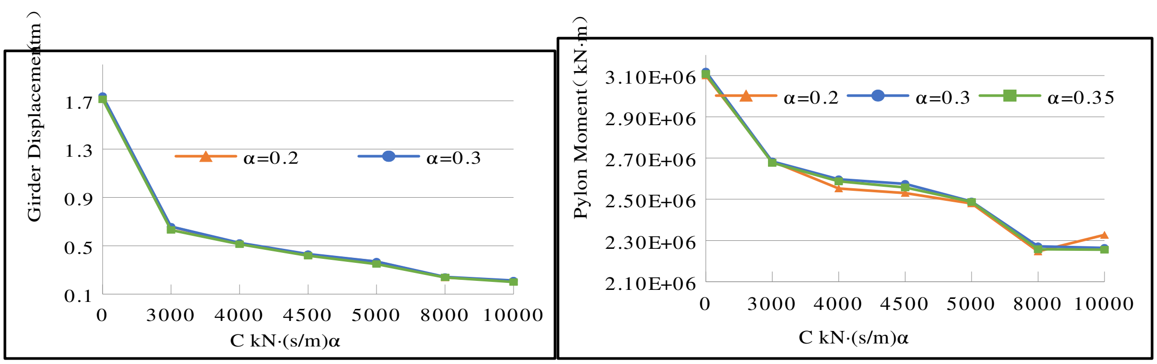

Figure 4 Effects of longitudinal damper parameters on girder-end displacement and pylon-base bending moment

Compared with the case without dampers, the girder-end relative displacement is reduced by 62% and the pylon-base bending moment by 14% when C=3000 $kN\cdot(s/m)^{\alpha}$. Excessively large damping coefficients lead to increased damper size and maximum damping force. Considering seismic performance and economy, two eddy current dampers are arranged at each girder end on both banks, with C=3000 $kN\cdot(s/m)^{\alpha}$ and α = 0.3. Two dampers with a critical maximum damping force of 1500 kN are connected in parallel at each support, resulting in four dampers per girder end.

(2) Parametric Analysis of BRB Central Buckle

The stiffness and yield strength of the energy-dissipation central buckle significantly affect the dynamic responses of the structure. Parametric sensitivity analyses were conducted on the yield strength, initial stiffness, and post-yield stiffness to provide a rational design basis for the central buckle. According to previous applications of BRBs, four groups of parameters were selected for comparison, with the dampers set as C=3000 $kN\cdot(s/m)^{\alpha}$ and α = 0.3.

Table 1 Calculation parameters of buckling-restrained brace central buckle

Central Buckle Set	Yield Bearing Capacity (kN)	Ultimate Bearing Capacity (kN)	Pre-yield Stiffness (kN/mm)	Post-yield Stiffness Ratio *a*
1	5000	7500	560	0.03
2	6000	9000	510	0.03
3	7000	10500	600	0.03
4	8000	12000	700	0.03

Table 2 summarizes the effects of the central buckle on the seismic responses. Compared with the case without a central buckle, installing the central buckle considerably improves the internal forces of the pylon: the pylon-base bending moment is reduced by approximately 20%, the shear force by 14%–16%, and the girder-end relative displacement by more than 40%. Within the parameter range, the variation of central buckle specifications has little effect on the pylon internal forces, while the girder-end displacement decreases slightly (within 3%) with increasing central buckle capacity.

Table 2 Parametric influence results of buckling-restrained brace central buckle

Central Buckle Set	Girder-end Relative Displacement (m)	Pylon Base Bending Moment (kN•m)	Pylon Base Shear Force (kN)	Central Buckle Axial Force (kN)
No central buckle	0.659	2683891	41707	—
1	0.39	2146798	35792	5553
2	0.386	2120433	35219	6732
3	0.381	2127595	35135	7639
4	0.374	2124660	34912	8732

The axial force of the central buckle increases with its capacity. Therefore, a lower capacity is preferred for economic and seismic reasons. Meanwhile, the central buckle should not yield under static loads and the E1 earthquake. Through comparative analysis, the yield strength of the central buckle is determined as 5000 kN, the core material is Q235B, and the initial stiffness is 824 kN/mm. Under the E1 earthquake, the internal force of the central buckle is 4102 kN, and under static loads, it is 3226 kN.

To reveal the force distribution between the central buckle and dampers, the seismic responses under the E2 earthquake for different configurations are compared in Table 3. Installing only the central buckle or only the dampers reduces the girder-end displacement by 62% and 64%, and the pylon-base bending moment by 14% and 19%, respectively. The combined system reduces the girder-end displacement by 77% and the pylon-base bending moment by 35%.

Table 3 Seismic response comparison of separate and combined energy dissipation devices

Case	Girder-end Displacement (m)	Pylon Base Bending Moment (kN·m)	Pylon Base Shear Force (kN)
No damper - No central buckle	1.718	3119120	48795
Only dampers	0.636	2658430	41707
Only central buckle	0.611	2506930	40984
Central buckle + Dampers	0.39	2007370	34934

4. Transverse Seismic System Design

4.1 Crossbeams with Corrugated Steel Webs

For the transverse seismic design of portal-frame pylons, the stiffness and self-weight of crossbeams dominate the overall transverse seismic responses. The three crossbeams of the Yalong River Special Bridge adopt a composite section of corrugated steel webs and prestressed concrete top and bottom slabs. This form fully utilizes the advantages of both materials, overcoming the insufficient shear capacity of concrete crossbeams and the complicated detailing and construction difficulties of steel crossbeams. Crossbeams with corrugated steel webs are lighter than concrete crossbeams, have lower axial stiffness, and retain high shear strength. This type of crossbeam has been successfully used in the Xingkang Dadu River Bridge on the Ya’an–Kangding Expressway. Seismic analysis shows that corrugated steel web crossbeams effectively reduce the overall transverse stiffness of pylons and decrease the transverse seismic responses by 25% compared with concrete crossbeams.

4.2 Energy-Dissipation Hollow Steel Braces

The lower pylon columns of the Xingkang Dadu River Bridge are 43 m high, while those of the Yalong River Special Bridge is 72.3 m. Coupled with the higher PGA under the E2 earthquake, further improvements in transverse seismic performance are required.

To control the excessive transverse seismic responses of the ultra-high lower pylon columns, hollow energy-dissipation tension-compression braces are installed at the pylon base and the lower crossbeam. These braces dissipate energy through axial deformation. Each brace consists of a base, top and bottom plates, and a web with diamond-shaped openings. The plates are bolted to the base, and the web is welded to the plates. Unlike conventional straight or cross braces, these braces are easy to replace after earthquake damage, enabling rapid functional recovery.

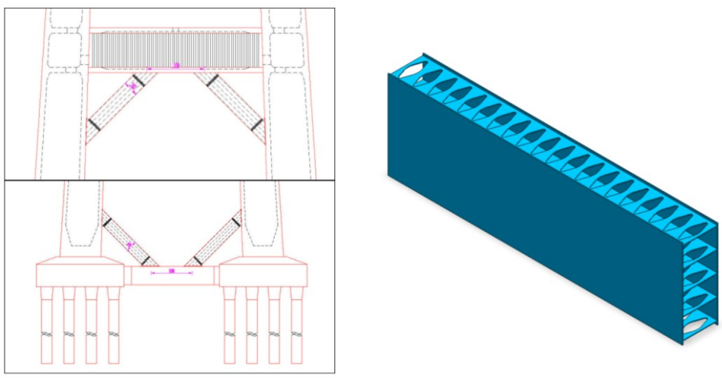

Figure 5 3D schematic of energy-dissipation hollow steel brace

4.3 Effect Analysis of Hollow Energy-Dissipation Braces

Time-history analyses were carried out to compare the effects of four configurations: no braces, braces at the pylon base only, braces at the lower crossbeam only, and braces at both locations. Internal forces at the lower crossbeam, ground tie beam, pylon column sections, pylon base, and pile cap were investigated. Three E2-level seismic waves were used, and ground motion was applied in the transverse and vertical directions.

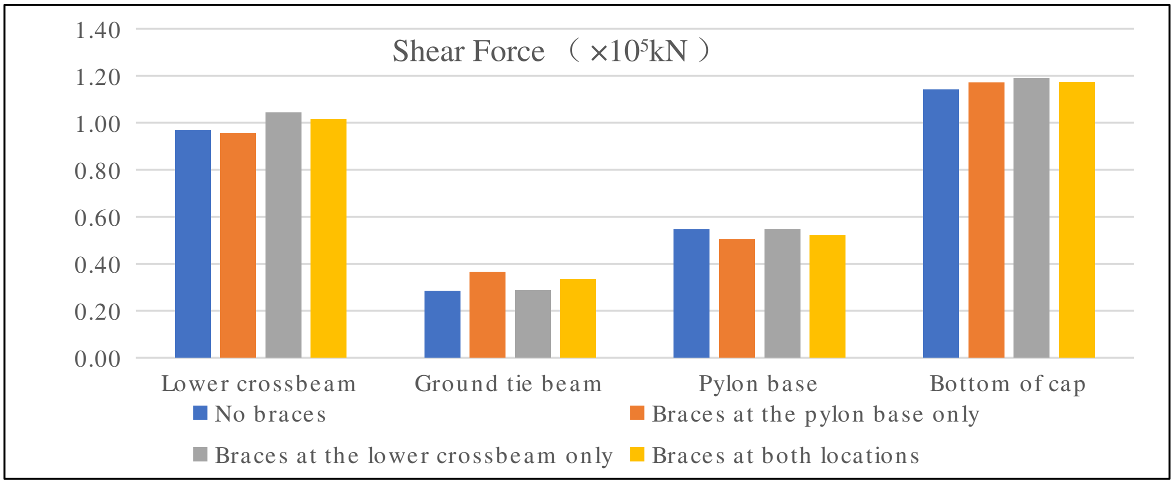

Figure 6 Shear forces of key sections with/without hollow energy-dissipation braces

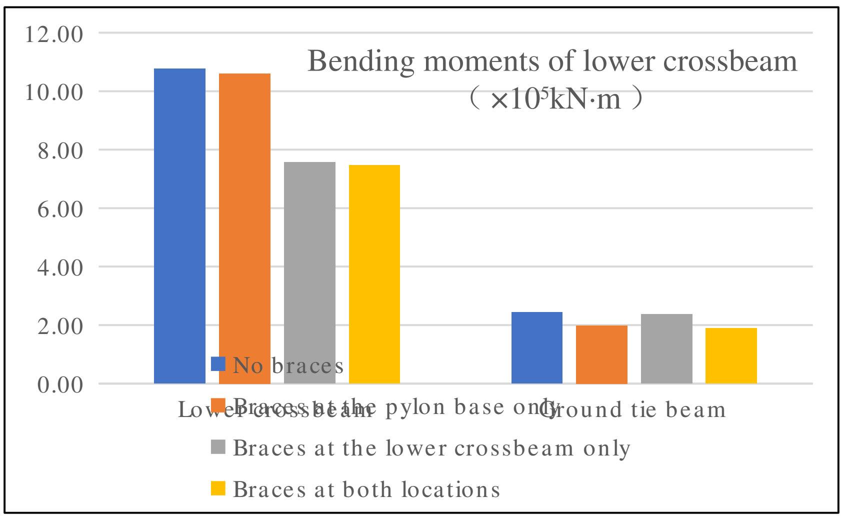

Figure 7 Bending moments of lower crossbeam and ground tie beam with/without hollow energy-dissipation braces

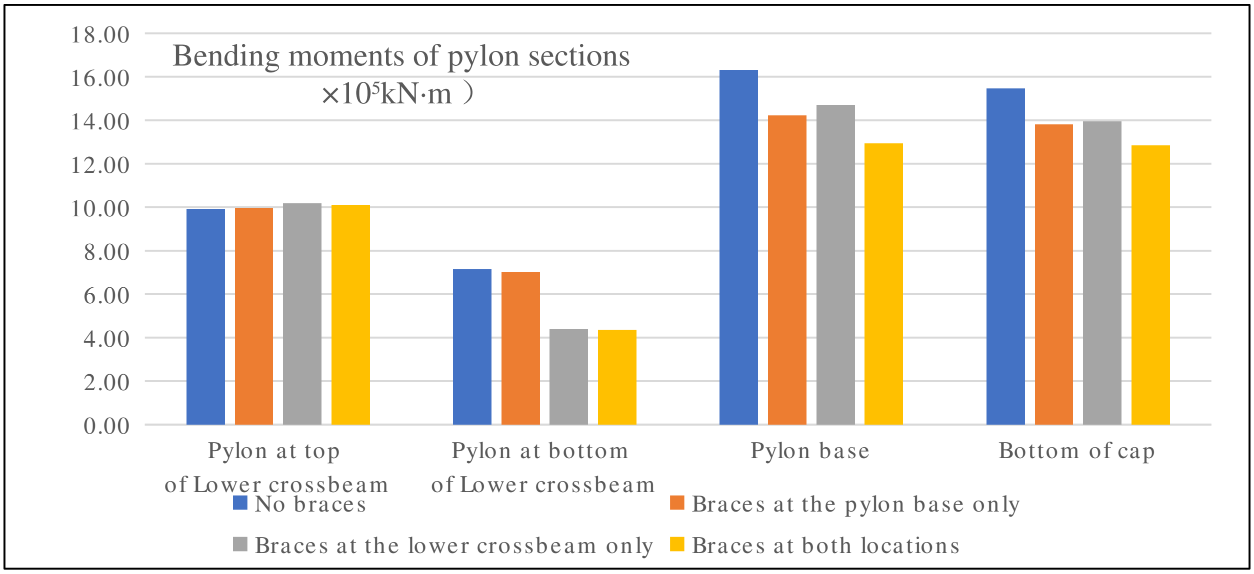

Figure 8 Bending moments of pylon sections with/without hollow energy-dissipation braces

The results indicate that installing braces at both the lower crossbeam and pylon base slightly increases the shear forces at the lower crossbeam, ground tie beam, and pile cap, but significantly reduces the transverse bending moments. Specifically, the bending moment of the lower crossbeam is reduced by 30.62%, that of the ground tie beam by 22.39%, that of the pylon base by 20.80%, and that of the pile cap by 17%.

5. Conclusions

(1) For ultra-high pylons in high-intensity seismic zones, the longitudinal seismic system combining an articulated energy-dissipation central buckle and girder-end eddy current dampers can effectively reduce the longitudinal seismic responses of pylons and the longitudinal displacements at girder ends.

(2) Installing only the central buckle or only the dampers reduces the girder-end displacement by 62% and 64%, and the pylon-base bending moment by 14% and 19%, respectively. The combined system reduces the girder-end displacement by 77% and the pylon-base bending moment by 35%.

(3) To improve the transverse seismic performance of pylons with ultra-high lower columns, installing two pairs of splayed steel braces between the lower pylon columns and the lower crossbeam and between the lower pylon columns and the pile cap tie beam can effectively reduce the transverse seismic responses. The bending moment of the lower crossbeam is reduced by 30.62%, and that of the pylon base by 20.80%.

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