Technical Note

Conceptual Design of Superspan Partial Ground-Anchored Cable-Stayed Bridge with Crossing Stay Cables

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Abstract: As the span of conventional cable-stayed bridges reaches 1,200 m or longer, accumulated horizontal force components of the stay cables cause huge axial pressure in the girder, leading to sharp increases of girder dimension and weight, which makes it difficult to compete with suspension bridges in terms of economic consideration. In this paper, a new type of cable-stayed bridge is proposed, namely the partial ground-anchored cable-stayed bridge with crossing stay cables. In this new cable-stayed bridge system, long stay cables cross with each other in the midspan zone of the main span while the other ends of the long cables are anchored to the ground in the side spans. By this design, the long cables result in no additional horizontal pressure to the main girder, and the ratio of pylon height to span length can be reduced. A comparative analysis of this new bridge system with a conventional self-anchored cable-stayed bridge with a main span of 1,408 m is carried out. Results show that by using the new bridge system, the horizontal pressure in the main girder can be reduced by 29.6%, and the total cost can be reduced by 11.8%. Furthermore, the size of ground anchors for this new bridge system is only about 30% of that of a suspension bridge with the same span length. Finally, a cantilever construction method for the new bridge system is introduced as well. **DOI: 10.1061/(ASCE)BE.1943-5592.0000534.** *© 2013 American Society of Civil Engineers.*

Author keywords: Cable-stayed bridge; Partial ground-anchored; Crossing stay cables; Static analysis; Dynamic performance; Horizontal pressure.

Introduction

The Russky Island Bridge, Sutong Bridge, and Stonecutters Bridge suggest that the cable-stayed bridge is a competent bridge concept for bridge main spans of more than 1,000 m. However, as span length increases, disadvantages of conventional self-anchored cable-stayed bridges are obvious.

1. The dimension and self-weight of the main girder will increase, eventually leading to increase of horizontal pressure in the girder; and
2. To provide efficient vertical support to the dead load as well as to maintain reasonable horizontal pressure in the girder, larger cable inclination angles are required, resulting in significantly increasing pylon height.

To overcome the problems of conventional cable-stayed bridges, the concept of the partially earth-anchored cable-stayed bridge was proposed by Gimsing (1988). Later, attempts were made by other researchers to improve this bridge system: Otsuka (1991) attempted to design hinges in the junction of the self-anchored girder and earth-anchored girder; Muller (1992) set prestress in the earth-anchored girder of main span; Xiao (1994) advised to pull the ends of side span; and Sun et al. (2010) presented its advantages in the construction-complete stage and conducted parametric analysis of static loading effects.

To extend the maximum span of the cable-stayed bridge, in this paper the partial ground-anchored cable-stayed bridge concept with crossing stay cables is proposed. Comparisons are made to a conventional self-anchored cable-stayed bridge with respect to static analysis, basic dynamic performance, and economic indicators. Construction feasibility of this new bridge concept is also illustrated by adopting a conventional construction method.

Concept of Partial Ground-Anchored Cable-Stayed Bridge with Crossing Stay Cables

The general idea of a partial ground-anchored cable-stayed bridge with crossing stay cables (named *the new bridge system* hereafter) is that long cables are crossed at the middle region of the main span (named *crossing cable region* hereafter, G6 in Fig. 1) and are ground-anchored at the side spans (Fig. 1).

As shown in Fig. 2, the tension forces T_{Li} and T_{Ri} in the two crossing stay cables (dotted lines in Fig. 2) supporting the same girder segment can be designed such that

1. The sum of vertical components of T_{Li} and T_{Ri} equals the weight of girder segment G_i; and
2. The horizontal component of T_{Li} equals that of T_{Ri}.

By this design, the two crossing stay cables generate no horizontal force to the main girder. Furthermore, the inclination angle of the long cables can be reduced and the height of pylons will be reduced correspondingly.

Calculation Models for the New Bridge System and Conventional Bridge System

To evaluate the basic performance of the new system, a new bridge system and a conventional cable-stayed bridge system with the same 1,408-m main span are designed, and finite-element models are

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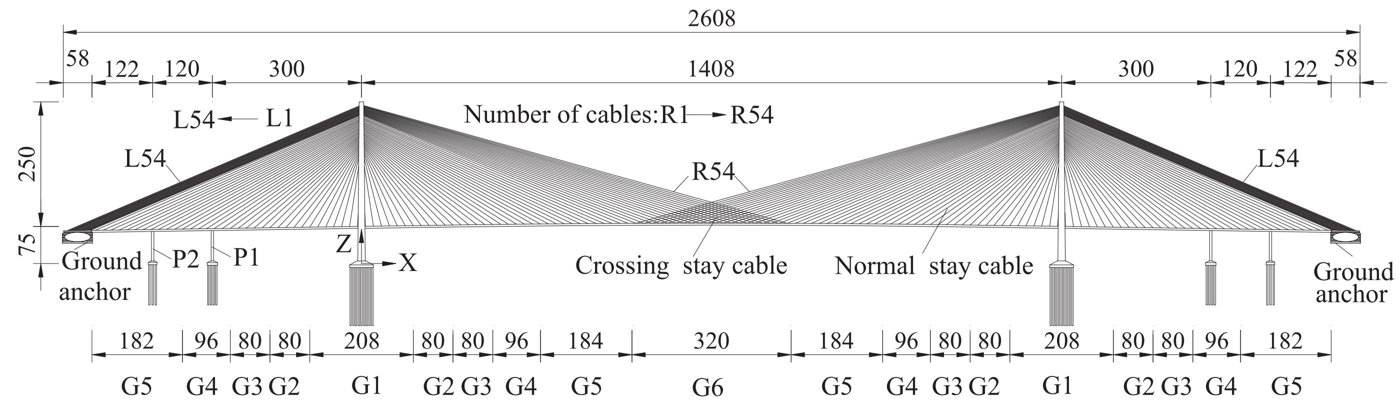

Fig. 1. Elevation layout of partial ground-anchored cable-stayed bridge with crossing stay cables (unit: meters); G1–G6 are girder section numbers with section properties summarized in Table 1

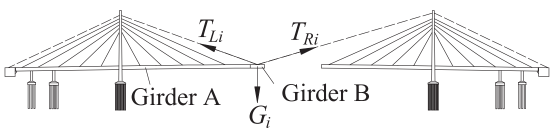

Fig. 2. Sketch of force balance of the new bridge system; Girder A is the self-anchored girder and Girder B is the ground-anchored girder

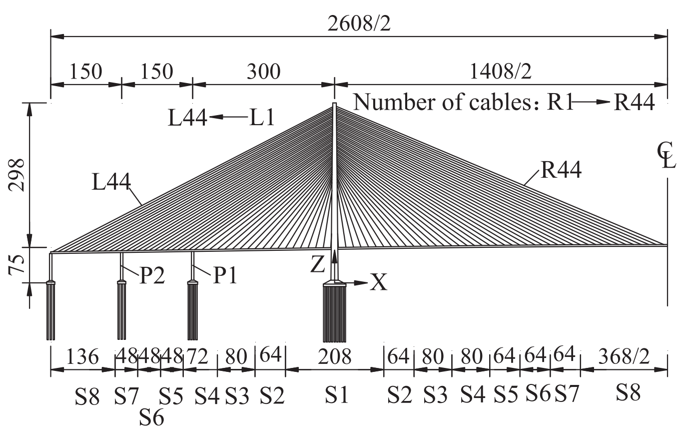

Fig. 3. Elevation view of self-anchored cable-stayed bridge (unit: meters); S1–S8 are the girder section numbers with section properties summarized in Table 1

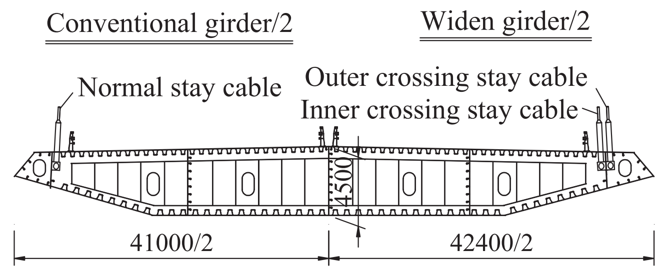

Fig. 4. Schematic of cross section of the main girder (unit: millimeters)

Table 1. Section Properties of Girder

Section	Area (m^2)	I_y (m^4)	I_z (m^4)
G1	2.19321	7.25612	299.948
G2	2.09676	7.18044	277.106
G3	1.98080	6.27521	286.803
G4	1.83587	6.29093	236.998
G5	1.67279	5.68910	219.764
G6	1.70476	5.77600	233.859
S1	3.13709	10.64670	405.491
S2	3.04594	10.25700	392.029
S3	2.88150	9.90611	378.570
S4	2.64146	8.98229	347.705
S5	2.47501	8.35051	325.910
S6	2.19321	7.25612	299.948
S7	1.98080	6.27521	286.803
S8	1.67279	5.68910	219.764

Note: I_y and I_z denote the moment of inertia.

created for both bridges. The following conditions and assumptions are used in the modeling process:

1. The traffic load grade used follows the Chinese code "General Code for Design of Highway Bridges and Culverts" (Ministry of Communications of P.R. China 2004), in which a lane load consists of a uniformly distributed load of 10.5 kN/m and a concentrated load of 360 kN;
2. The secondary dead load is 62.5 kN/m;
3. The yield stress of cables is 1860 MPa;
4. The steel grade for the main girder is Q345qD with a yield stress of 345 MPa; and
5. The pylon concrete grade is C50 with a design compressive strength of 22.4 MPa.

The new bridge system and the conventional system are shown in Figs. 1 and 3, respectively, both with inverted Y-shaped pylons. The 4.5-m-deep main girder is continual all along the spans and fully floating in the longitudinal direction. A schematic of the cross section of the main girder is shown in Fig. 4 with detailed parameters summarized in Table 1.

Static Effects

Effects in Bridge Completion Stage

Fig. 5 shows the comparison of axial force in the girder. The origin of the horizontal axis in Fig. 5 is the same as the x-axis in Figs. 1 and 3. It

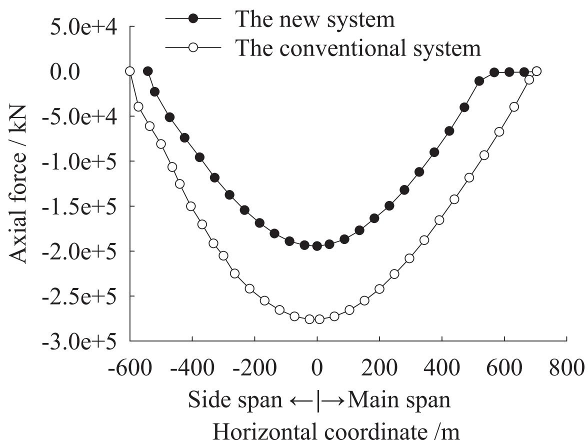

Fig. 5. Axial force of the girder under the effect of dead load

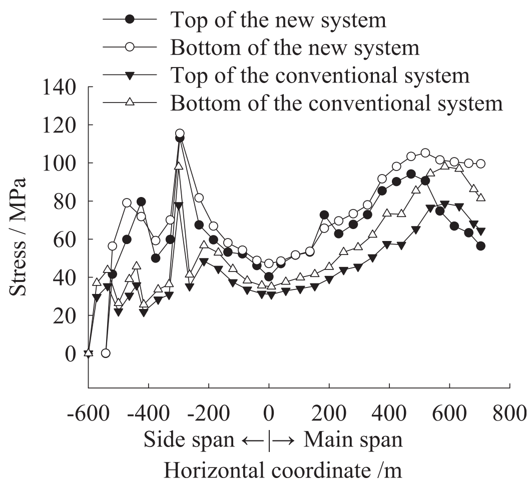

Fig. 6. Stress amplitude of the girder under the effect of traffic load

can be clearly seen that the maximum axial pressure in the main girder of the new bridge system, which is 1.94×10^5 kN, is significantly smaller than that in the conventional bridge system, 2.76×10^5 kN.

Effects in Operation Stage

Under the combined effect of dead load and traffic load, the maximum compressive stress of the main girder in both bridge systems appears at the auxiliary pier near the pylons. The maximum compressive stress at the top and bottom of the girder is 123 and 139 MPa, respectively, for the new bridge system, compared with 123 and 136 MPa for the conventional bridge system. The maximum tensile stress in the girder in the two bridge systems is 72 and 64 MPa, respectively.

As shown in Fig. 6, the maximum stress amplitude of the girder is 115 MPa for the new bridge system and 98 MPa for the conventional bridge system under the effect of traffic load, both being smaller than the allowable stress amplitude of Q345qD (172 MPa). All the cables supporting the girder are anchored on the pylons in the new bridge system (unlike the Dischinger system, in which some of the cables are anchored on pylons and others are anchored on main cables). By this design, the support stiffness by cables near the junction does not change abruptly, and the stress amplitude of the junction will have only a slight increase that will not cause fatigue problems under traffic load.

Under combined effect of dead load and traffic load, pylons in both systems are under compressive stress, with the maximum stress occurring at the intersection of pylon and crossbeam under the main girder, which is 12.5 and 12.6 MPa for the new bridge system and conventional bridge system, respectively.

The stress in the cables in both systems appears to vary in the range between 518 and 743 MPa under combined effect of dead load and traffic load, smaller than the allowable stress of 744 MPa. Meanwhile, the maximum stress amplitude in the cables is 200 MPa, smaller than the allowable stress amplitude of 250 MPa.

Basic Dynamic Performance

The first few vibration modes of the two systems are shown in Figs. 7 and 8. As shown in the figures, for both systems the fundamental vibration mode is the girder's lateral symmetric bending mode, indicating that the transverse stiffness is the key fact for the dynamic performance of the two systems. The second mode of the conventional system is the girder's longitudinal floating, which corresponds to the sixth vibration mode for the new system owing to the longitudinal restraint of the anchors. Reduction in sizes of the cables and girder in the new system leads to decrease in the vibration frequencies of the girder's lateral symmetric bending, symmetric torsion, and vertical symmetric bending modes. The frequency of the pylon's lateral bending of the new system is higher than that of the conventional system, which is influenced by the height of pylons.

Estimate of Material Consumption

Table 2 shows the amount of materials used in both systems. The comprehensive unit prices come from the reference of Xu (2005). Compared with the conventional bridge system, use of steel in the girder in the new system is reduced by 22.1% because of the smaller horizontal force; the amount of concrete consumed for the pylons is reduced by 18.1% because of the decrease of pylon height and girder weight, although the material use of cables increases by 16.1%. What is more, the consumption of ballast in the side spans can be reduced by two thirds. Table 2 shows that the new system has significant economic advantage and can save 11.8% of the total investment compared with the conventional bridge system.

The two added anchors have a major impact on the economy of the new bridge system. Under the combined effect of the dead load and traffic load, the maximum horizontal force transmitted to one anchor is 167.0 MN in this example. For the purpose of comparison, the 4th Changjiang River Bridge, a suspension bridge with a main span of 1,418 m located in Nanjing, is used here. The maximum horizontal force on the anchor, transmitted from the two main cables, is calculated to be 525.4 MN based on the information provided by Cui et al. (2010). Further calculation indicates that the maximum horizontal force on the new bridge system is only 30% of that of a suspension bridge with the same main span length.

Construction Method

The ground-anchored girder can be constructed by using the cantilever method step by step. A deck derrick crane can be used to elevate the beam segment, as shown in Fig. 9. The ground-anchored girders are erected after the self-anchored girders by using the normal cantilever method. To ensure that the ground-anchored girders will not cause additional horizontal pressure on the self-anchored girders, the short (CS) and long (CL) crossing stay cables are pulled at the same time during construction. A towing rope is

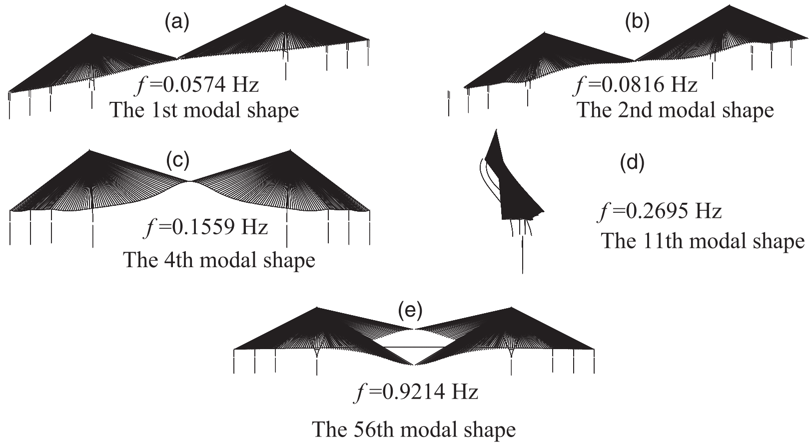

Fig. 7. Parts of vibration modes of the conventional system: (a) lateral symmetric bending of the girder; (b) longitudinal floating of the girder; (c) vertical symmetric bending of the girder; (d) lateral bending of the pylons; (e) symmetric torsion of the girder

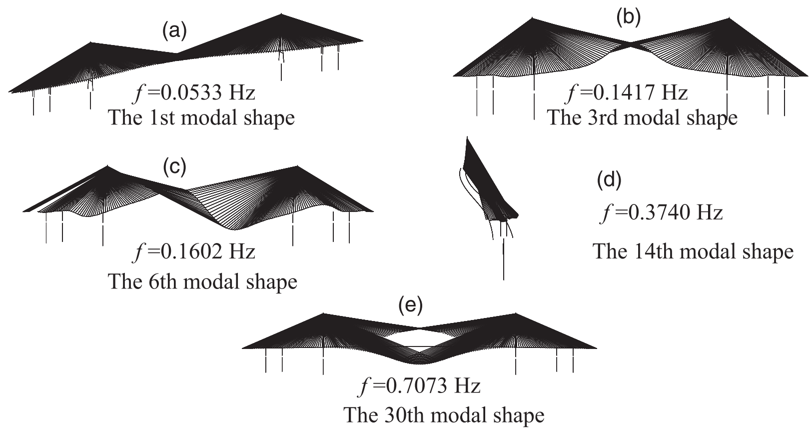

Fig. 8. Parts of vibration modes of the new bridge system: (a) lateral symmetric bending of the girder; (b) vertical symmetric bending of the girder; (c) longitudinal floating of the girder; (d) lateral bending of the pylons; (e) symmetric torsion of the girder

Table 2. Material Consumption and Cost Breakdown of the Two Different Bridge Systems (1 CNY ≈ US$0.16)

Item	Unit	Comprehensive unit price (CNY)	New system (A) Quantity	New system (A) Cost (10,000 CNY)	Conventional system (B) Quantity	Conventional system (B) Cost (10,000 CNY)	Cost difference, (B − A)	Ratio of cost difference, (B − A)/B (%)
Concrete foundation	m^3	2,240	291,181	65,225	336,082	75,282	10,058	13.4
Concrete pylon	m^3	2,350	67,350	15,827	82,229	19,324	3,497	18.1
Concrete anchor	m^3	1,300	59,027	7,673	0	0	− 7,673	0
Cable	t	26,500	10,177	26,970	8,764	23,226	− 3,744	− 16.1
Girder	t	14,000	47,371	66,319	60,824	85,154	18,835	22.1
Ballast	t	3,500	5,204	1,821	15,540	5,439	3,617	66.5
Total cost	10,000 CNY			183,836		208,425	24,589	11.8

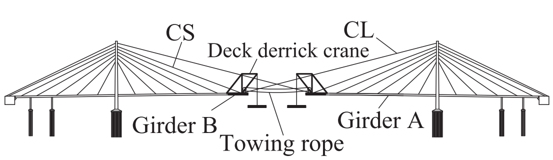

Fig. 9. Sketch of construction method of the new bridge system; Girder A is the self-anchored girder and Girder B is the ground-anchored girder

used to haul the crossing stay cable CL across the center region of the main span before it is anchored to the girder.

Conclusion

The proposed new bridge system has obvious advantages over self-anchored cable-stayed bridges in the following aspects:

1. The horizontal pressure in the main girder caused by cables is reduced significantly;

2. The new system has considerable savings in material and therefore in total cost; and
3. The new bridge system makes the following tasks much easier: welding of girder plates, design of girder for holding ballast at the side spans, and construction of the high pylons.

Moreover, this study shows that the new cable-stayed bridge system can be constructed using the conventional cantilever method.

Every kind of bridge has its own applicable conditions and span range. For example, the conventional cable-stayed bridge system may perform better than the new bridge system when the foundation soil is soft or when the anchors are located in deep water. Further research is needed in the following aspects of the new bridge system: nonlinear effects, performance under wind, and earthquake loading.

Notation

The following symbols are used in this paper:

C50 = a grade of concrete whose design compression strength (with 150-mm cube) is 50 MPa; and

Q345qD = a type of steel material in China with a yield strength of 345 MPa.

References

Cui, B., et al. (2010). "The summary design of the 4th Changjiang River Bridge in Nanjing City." *2010 National Academic Symp. on Bridges*, China Communications Press, Beijing.

Gimsing, N. J. (1988). *Cable-stayed bridges with ultra long spans*, Dept. of Structural Engineering, Technical Univ. of Denmark, Lyngby, Denmark.

Ministry of Communications of P.R. China. (2004). "General code for design of highway bridges and culverts." *JTG D60-2004*, China Communications Press, Beijing.

Muller, J. (1992). "The bi-stayed bridge concept: Overview of wind engineering problems." *Proc., 1st Int. Symp. on Aerodynamics of Large Bridges,* Transportation Research Board, Washington, DC.

Otsuka, H. (1991). "Fundamental study for design and erection of partially anchored composite cable-stayed bridge with 900 m center span length." *Innovation in cable-stayed bridge, Proc., Int. Symp. for Innovation in Cable-Stayed Bridges*, Fukuoka, Japan.

Sun, B., Cheng, J., and Xiao, R. C. (2010). "Preliminary design and parametric study of 1400 m partially earth-anchored cable-stayed bridge." *Sci. China Technol. Sci.*, 53(2), 502–511.

Xiao, Y. (1994). "Tensioning of cable-stayed bridge girder for increased span length and improved stability." *Proc., Int. Symp. & Exhibition on Cable-Stayed Bridges*, Tongji Univ., Shanghai, China.

Xu, Z. Y. (2005). "The cost determination and control of Runyang Yangtze River Highway Bridge." Master's thesis, Tongji Univ., Shanghai, China.