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Study on design parameters of leaning-type arch bridges

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Abstract. Leaning-type arch bridge is a new spatial structural system composed of two vertical arches and two leaning arches. So far there has been no contrast analysis of leaning type arch bridge with different systems. This paper focus on a parametric study of leaning type arch bridge with different systems to find the influential rules on structural forces and stability and to provide some reference for practical designs. The parametric analysis is conducted with different rise-to-span ratios and bending rigidities of arch ribs by comparing internal forces. The internal forces decline obviously with the increase of the rise-to-span ratio. The bending moments at the centers of the main arches and the leaning arches are sensitive to the bending rigidities of arch ribs. Parametric studies are also carried out with different structural systems and leaning angles of the leaning arch by comparing the static stability. The lateral stiffness of leaning-type arch bridge is less than the in-plan stiffness. Compared with the leaning-type arch bridge without thrust, the leaning-type arch bridge with thrust has a lower stability safety coefficient. The stability safety coefficient rises gradually with the increase of inclining angle of the leaning arch. This study shows that the rise-to-span ratio, bending rigidities of arch ribs, structural system and leaning angles of the leaning arch are all critical design parameters. Therefore, these parameters in unreasonable range should be avoided.

Keywords: leaning-type arch bridge; parametric analysis; rise-to-span ratio; bending rigidities of arch ribs; leaning angle of the leaning arch

1. Introduction

At present, for short and medium-span bridges located in urban environments, the aesthetic quality may be a desired, or even the primary object of bridge designers (Jorquera-Lucerga 2013). A lot of spatial arch bridges which have been landmarks of the cities are good examples expressing this aesthetic approach, such as leaning type arch bridge, butterfly arch bridge, basket handled bridge, etc (Guo *et al*. 2014, Manterola *et al*. 2011). Besides aesthetic characters of these spatial arch bridges, the structural behavior of them has attracted the specialists' attention (Gui *et al*. 2016, Lu *et al*. 2009, Marta *et al*. 2012).

Among these special arch bridges, leaning-type arch bridge composed of two vertical arches and two leaning arches is competitive in wide urban bridges because it has concise and unique structural form, and tries to give the same importance to the traffic as to the pedestrian. The first leaning-type arch bridge in the world is Bace Roda Bridge, designed by Santiago Calatrava, built in 1987 in Barcelona with a 52-meter length and a 25.8-meter width (Cerver 1996). Over the past decades, leaning-type arch bridges have been developing rapidly. At present, more than 20 leaning-type arch bridges have been built around the world, most of them in China (Liu *et al*. 2014).

Leaning-type arch bridges have not only general characteristics of combinatorial bridge with beam and arch but also an obvious three-dimensional effect. The design concept and the structural analysis method of the leaning-type arch bridge have their own characteristics. However, on account of that some important design parameters are not reasonable enough, several leaning-type arch bridges being built cannot give full play to the advantages of this type of bridge and cause the waste of structural materials. For example, a leaning-type arch bridge with a span length of 120m cannot keep self-balance after completion because the angle between the main arch and the leaning arch is not reasonable. The thrust from the leaning arch is so large that it makes the main arch having an outward tilt of one degree in the original design convert to an outward tilt of 0.5 degree after completion (Chen *et al*. 2007). Therefore, it is necessary to study the main design parameters of leaning-type arch bridges to find out some influential rules on structural forces and stability and provide some reference for practical designs.

Xiao *et al*. (2004) investigated the key technical problems including the structural system, mechanical characteristic, detailed conformation and erection process of leaning-type arch bridges. Chen and Sun (2009) investigated the influence of structural parameters on the static characteristics and stability of leaning-type arch bridges. Liu *et al*. (2014) constructed a numerical model of the main members of leaning-type arch bridge and obtained some analytical solutions for lateral buckling critical load of the leaning-type arch bridge based on the Ritz method. Liu *et al*. (2015) investigated the ultimate bearing capacity for a single arch, a parallel arch, and leaning arch systems with a 10, 20, and 30-degree inclining angles between the main

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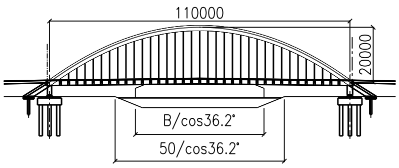
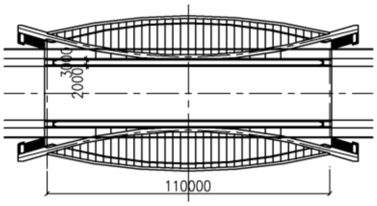
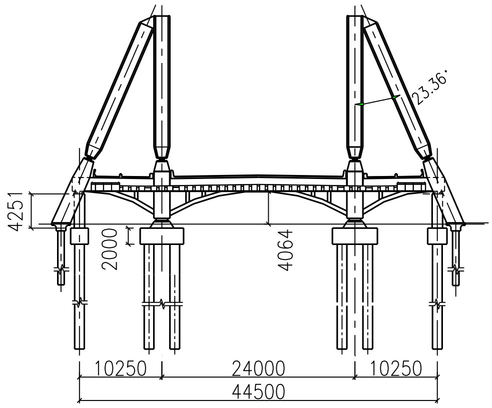


(a) Elevation



(b) Plan



(c) Cross section

Fig. 1 General arrangement diagram

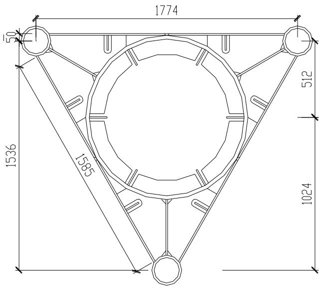


Fig. 2 Cross section of arch rib

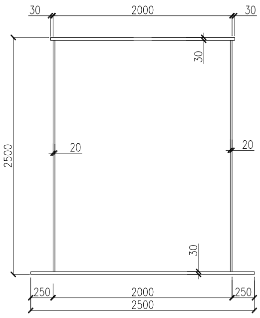


Fig. 3 Cross section of main beam

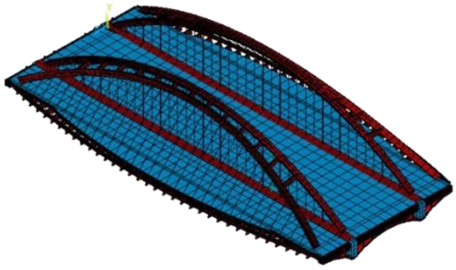


Fig. 4 Model A

and the leaning arches.

However, so far there has been no contrast analysis of leaning type arch bridge with different structural systems with thrust and without thrust. This paper focus on a parametric study of leaning type arch bridges with the two different systems to find out some influential rules on the structural forces and stability and to provide some reference for practical designs. The parametric analysis is conducted with different rise-to-span ratios and rigidities of arch ribs by comparing the internal forces. Different structural systems and leaning angles of the leaning arch are also considered with the comparison on static stability.

2. Background: a leaning-type arch bridge

2.1 Description

This study takes Yufeng Bridge in Kunshan China as the engineering background with the general arrangement diagram shown in Fig. 1. The main bridge is 110 m long with a varying width of 48.0m at the main piers to 60.9m at the bridge center. The main arches are in vertical planes, while the leaning arches have 23.26° leaning angles. All of the main arches and the leaning arches have parabolic axes. The in-plan rise-to-span ratio of the main arch is 1/5.5, and that of the leaning arch is 1/5.4. Sections of arch ribs are all equilateral triangles. The sections of main arch and leaning arch are same which can be seen in Fig. 2. The main arch ribs are concrete filled steel tubes with high resistance against compression and bending moment. However, the leaning arch ribs are not filled with concrete to reduce the self-weight.

The main arches and leaning arches are beam and arch combined structures. In order to overcome the horizontal thrust arising from the dead load and the live load, strong main beams (Fig. 3) and cable ties are chosen as the tie bars between the ends of the main arches and the leaning arches, respectively. The end cross beams combine the main arches with the leaning arches as a whole in the horizontal direction and bear the lateral horizontal force from the leaning arches.

2.2 Finite element modeling

Two different finite-element models are established in ANSYS (Figs. 4-5). Based on Kunshan Yufen Bridge, a spatial model without thrust (Model A) has been established. The main arch ribs, leaning arch ribs, crossing braces, main girders, end crossing beams, small longitudinal girders, and the substructures of the main bridge are simulated as spatial beam elements. The deck slabs are

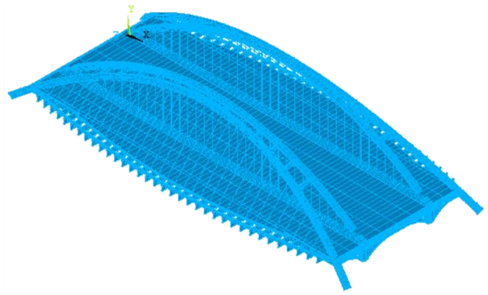


Fig. 5 Model B

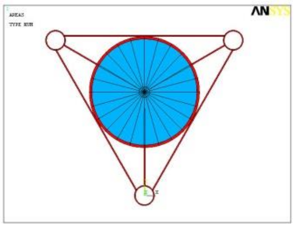


Fig. 6 FEM of cross section of the main arch rib

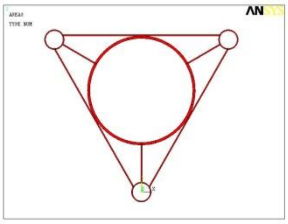


Fig. 7 FEM of cross section of the leaning arch rib

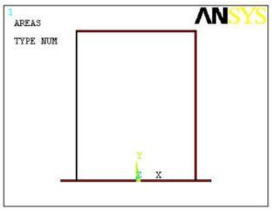


Fig. 8 FEM of cross section of the main beam

modeled with spatial shell elements. The hangers and the ties of the leaning arches are modeled with truss elements. Models of the main arch ribs, leaning arch ribs, the main beams sections are shown in Figs. 6-8, respectively, in which the main arch ribs are modeled with user-defined steel-concrete composite cross-sections in Beam188 elements and the material properties are accordingly correctly simulated (Chinese concrete C40, steel Q345).

There are 8 bearings set in Model A. The bearings of main arches include one fixed bearing, one bidirectional sliding bearing and two unidirectional sliding bearings. The leaning arches have four bidirectional sliding bearing. The positions of these bearings are shown in Fig. 9 and the degree of freedom of every bearing are listed in Table 1.

As a contrast to Model A, Model B is established by extending the leaning arches to the ground and changing the leaning arches into non-hinged structures with thrust. Accordingly, four bearings of leaning arches in Model B are all fixed.

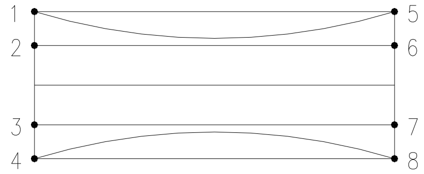


Fig. 9 Position of boundary conditions

Table 1 Boundary conditions in Model A

DOF \ No.	1	2	3	4	5	6	7	8
*X**	0**	1	1	0	0	0	0	0
Y	1	1	1	1	1	1	1	1
Z	0	1	0	0	0	1	0	0
θ_x	0	0	0	0	0	0	0	0
θ_y	0	0	0	0	0	0	0	0
θ_z	0	0	0	0	0	0	0	0

**X*: Longitudinal direction, *Y*: Vertical direction, *Z*: Lateral direction
**Boundary conditions: 1: fixed, 0: free

To obtain the comparison of the structural responses of Model A and B under the same conditions, the following assumptions are made in the following parametric studies:

(1) The structural elements of the leaning arch bridge model with thrust adopt the same properties as that of the bridge without thrust.

(2) The full scaffold method is adopted as the construction method.

Based on Model A, the authors analyzed the internal forces of Yufeng Bridge. Because the tensile forces in hangers are critical to the internal forces and displacements of the arch bridge, the authors have compared the compute data with the test data of tensile forces of hangers along the two main arches in the finished state to testify the reliability of Model A as shown in Table 2 (Li 2006). The absolute values of comparative errors between the compute values and the test values of tensile forces in hangers are less than 5%, except for a short hanger of which the error is -5.9%. This indicates that the compute value of Model A is reliable.

3. Parametric study on internal forces

The bridge spans concerned in this paper are only around 110 m and aerodynamic problems are unlikely to occur. Therefore, the authors mainly focus on the parameters that influence the static behaviors of leaning-type arch bridges in this study.

3.1 Effect of rise-to-span ratio

The rise-to-span ratio is a key parameter in arch bridges, which not only affects the internal forces and stability, but also influences the choice of construction methods. For simple arch bridge, under the dead loads, the ratio of the horizontal thrust to vertical reaction force increases with the decrease of the rise-to-span ratio. Similarly, the internal

Table 2 Comparison between the compute data and the test data of tensile forces of hangers (kN)

No.	Compute data	Test data - Arch 1		Test data - Arch 2	
		Force	Error	Force	Error
1	709	684	-3.5%	675	-1.3%
2	614	578	-5.9%	593	2.6%
3	650	666	2.5%	639	-4.1%
4	647	642	-0.8%	642	0.0%
5	646	621	-3.9%	636	2.4%
6	648	636	-1.9%	656	3.1%
7	652	634	-2.8%	646	1.9%
8	657	643	-2.1%	664	3.3%
9	649	637	-1.8%	629	-1.3%
10	660	648	-1.8%	634	-2.2%
11	660	656	-0.6%	640	-2.4%
12	659	640	-2.9%	633	-1.1%
13	666	647	-2.9%	651	0.6%
14	663	672	1.4%	686	2.1%
15	665	642	-3.5%	651	1.4%
16	663	641	-3.3%	648	1.1%
17	666	639	-4.1%	645	0.9%
18	659	655	-0.6%	652	-0.5%
19	660	668	1.2%	654	-2.1%
20	660	634	-3.9%	657	3.6%
21	649	646	-0.5%	660	2.2%
22	657	656	-0.2%	672	2.4%
23	653	675	3.4%	630	-6.7%
24	648	675	4.2%	636	-5.8%
25	646	666	3.1%	655	-1.7%
26	647	652	0.8%	676	3.7%
27	650	670	3.1%	669	-0.1%
28	614	627	2.1%	620	-1.1%
29	709	676	-4.7%	689	1.9%

forces of the leaning-type arch bridge under the dead loads will be affected obviously by the variation of the rise-to-span ratio. Two models are used to investigate the effect of rise-to-span ratio on the internal forces of main structural elements such as main arches, main beams and leaning arches under different loads. Eight cases with different rise-to-span ratio in the two models are studied. It is assumed that the main arches and leaning arches always adopt parabolic axes with the variation of rise-to-span ratio and the rise of the leaning arch changes in accordance with structural configuration.

3.1.1 Leaning-type arch bridge without thrust

Case 1 to case 4 have different rise-to-span ratios of main arches from 1/8 to 1/5 for the leaning-type arch bridge without thrust in Model A. The ratios of the internal forces of other cases to those of case 3 with a rise-to-span ratio of 1/6 can be seen in Table 3. The comparisons of the internal force ratios in the four cases are shown in Fig. 10.

It can be seen that the internal forces at the bridge center under the dead load in Model A drop evidently with the increase of rise-to-span ratio. The internal force ratios

Table 3 Internal force ratio of leaning-type arch bridge without thrust under dead loads

Case	Rise-to-span ratio (f/l)	Main arch center		Main beam Center		Leaning arch center	
		Axial force	Moment	Axial force	Moment	Axial force	Moment
1	1/8	1.85	1.69	1.34	1.73	1.39	1.58
2	1/7	1.16	1.27	1.17	1.33	1.20	1.29
3	1/6	1.00	1.00	1.00	1.00	1.00	1.00
4	1/5	0.83	0.76	0.84	0.74	0.93	0.70

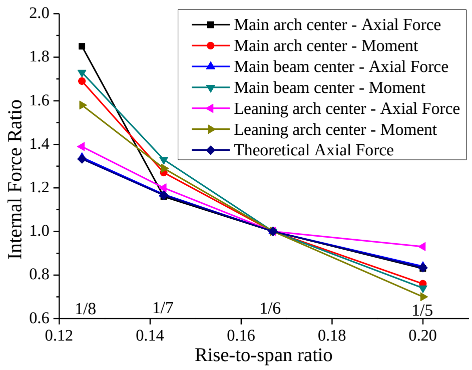


Fig. 10 Effect of rise-to-span ratio on internal force ratios at bridge center under dead loads in Model A

Table 4 Internal force ratio of leaning-type arch bridge with thrust under dead loads

Case	Rise-to-span ratio (f/l)	Main arch center		Main beam Center		Leaning arch center	
		Axial force	Moment	Axial force	Moment	Axial force	Moment
5	1/8	1.32	1.61	1.24	1.69	1.38	1.64
6	1/7	1.16	1.24	1.12	1.32	1.19	1.32
7	1/6	1.00	1.00	1.00	1.00	1.00	1.00
8	1/5	0.84	0.78	0.88	0.77	0.81	0.64

decline sharply with rise-to-span ratio increasing from 1/8 to 1/7. During this period, the most rapid decrease in all of the internal forces is the axial force ratio at the main arch center. Though the declining rates of internal force ratios are not so rapid with rise-to-span ratio increasing from 1/7 to 1/5 compared with that from 1/8 to 1/7, they are indeed remarkable and impressive.

3.1.2 Leaning-type arch bridge with thrust

In this section, the internal forces of main structural members of the leaning-type arch bridge model with thrust under dead loads are calculated. Case 5 to 8 are for Model B and have different rise-to-span ratios of main arches from 1/8 to 1/5. The ratios of the internal forces of case 5-8 to those of case 7 with a rise-to-span ratio of 1/6 are shown in Table 4. The effects of the rise-to-span ratio on internal force ratios at the bridge center are shown in Fig. 11.

Figs. 10 and 11 reflect approximately the same trends that the internal force ratios decline obviously with the increase of rise-to-span ratio and drop most sharply with rise-to-span ratio increasing from 1/8 to 1/7. However, there

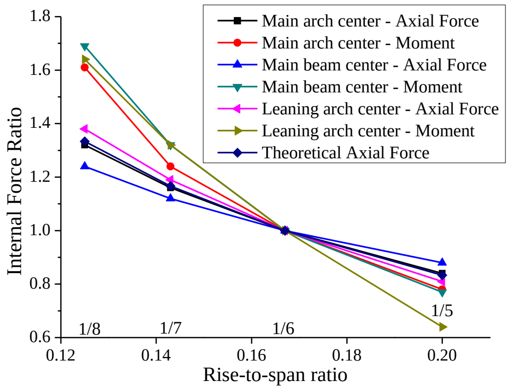


Fig. 11 Effect of rise-to-span ratio on internal force ratios at bridge center under dead loads in Model B

are some differences. The most significant one is that the effects of rise-to-span ratio on moment ratios are more obvious than on axial force ratios at the bridge center of leaning-type arch bridge with thrust. To sum up, with the rise-to-span ratio increasing from 1/8 to 1/5, although internal forces of the main arches and beams in Model A decline more slowly than that in Model B, internal forces of the leaning arches in Model A drop more rapidly than that in Model B.

3.1.3 Theoretical approach

It is well known that the compressive force at the center of an arch in a simple arch, or both the compressive force in the arch and the tension in the tie bar at the bridge center in a tied arch, can be expressed as

$$H = \frac{ql^2}{8h} \tag{1}$$

where H represents the horizontal force at the bridge center, q represents the uniformly distributed force along the horizontal projection line of the arch, l represents the span of the arch and h represents the rise of the arch.

As an immediate result of Eq. (1), the axial force ratio in section 3.1.1 and 3.1.2 must be the reciprocal of the rise-to-span ratio. This is also displayed in both Fig. 10 and 11, and the values are 1.33, 1.17, 1.00 and 0.83. It can be seen that the tendency of all lines representing axial forces are the same. However, due to the complexity of the real bridge structure, the values are somehow discrete.

3.2 Effects of bending rigidities of arch ribs

The main arch of Yufeng Bridge is a composite structure with stiff-beam and stiff-arch. The in-plan bending rigidity ratio of the main beam to that of the main arch rib is 3.076. As a contrast, the leaning arch is a composite structure with flexible-tie and stiff-arch. For a composite bridge with stiff-beam and stiff-arch, the bending moments under various loads distribute in the beam and arch according to their bending rigidity ratio. An appropriate rigidity ratio should be chosen to obtain a good distribution of the internal forces in the main beams and arches. This section brings forward a parametric study of the effects of bending rigidities of arch ribs on the internal forces at the bridge center.

In the following analysis, it is assumed that the sectional areas of beams and arches and the bending rigidity of main beams remain unchanged and the bending rigidities of the main arch ribs and the leaning arch ribs vary with same ratios.

Table 5 Internal force ratio of leaning-type arch bridge without thrust under dead loads

Bending rigidities of arch ribs (I)	Main arch center		Main beam Center		Leaning arch center	
	Axial force	Moment	Axial force	Moment	Axial force	Moment
1/5	1.01	0.33	0.98	1.01	0.98	0.30
1/4	1.01	0.37	0.98	1.01	0.98	0.35
1/3	1.01	0.44	0.99	1.01	0.98	0.43
1/2	1.01	0.58	0.99	1.00	0.99	0.59
1	1.00	1.00	1.00	1.00	1.00	1.00
2	0.99	1.81	1.01	1.00	1.02	1.69
3	0.98	2.61	1.02	1.00	1.03	2.28
4	0.98	3.42	1.03	1.01	1.04	2.81
5	0.97	4.24	1.03	1.02	1.05	3.30

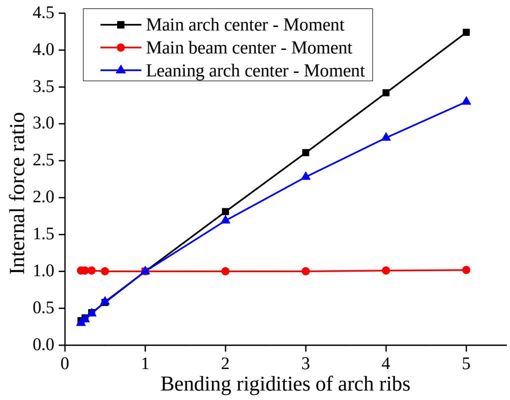


Fig. 12 Effects of arch rigidity on internal force ratio at bridge center under the dead loads in Model A

3.2.1 Leaning-type arch bridge without thrust

It is assumed that the bending rigidities of arch ribs of Yufeng Bridge is cardinal number 1, and the internal forces of the main arch, main beam and leaning arch of Model A under the dead loads are calculated as cardinal number 1. The internal force ratios with different bending rigidities of arch ribs can be seen in Table 5 and Fig. 12. Due to the same reason as shown in Eq. (1), the variation of bending rigidities of arch ribs has minor effects on the axial force of the structure. The main beam and main arch are hinged and tensions in hangers are determined to obtain a reasonable condition under the dead loads. As a consequence, bending moments at the main beam center is not sensitive to the variation of bending stiffness of arch ribs.

The moment at the main arch center increases linearly with the bending rigidities of arch ribs, and it has the most rapid growth rate among all of the internal forces. The moment at the main arch center increases approximately 0.8

Table 6 Internal force ratio of leaning-type arch bridge with thrust under dead loads

Bending rigidities of arch ribs (I)	Main arch center		Main beam Center		Leaning arch center	
	Axial force	Moment	Axial force	Moment	Axial force	Moment
1/5	1.01	0.35	0.97	1.05	0.97	0.29
1/4	1.01	0.39	0.97	1.05	0.97	0.34
1/3	1.01	0.46	0.98	1.04	0.98	0.42
1/2	1.01	0.60	0.98	1.03	0.98	0.58
1	1.00	1.00	1.00	1.00	1.00	1.00
2	0.99	1.76	1.02	0.97	1.02	1.68
3	0.98	2.50	1.03	0.96	1.04	2.24
4	0.97	3.25	1.04	0.96	1.05	2.72
5	0.97	4.01	1.04	0.96	1.06	3.16

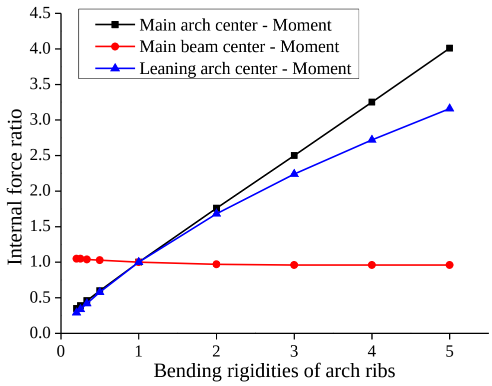


Fig. 13 Effects of arch rigidity on internal force ratio at bridge center under the dead loads in Model B

times with the bending rigidity increasing every one time. As to the moment at the leaning arch center, the general trend appears to be nonlinear increase with a less rate than that of the main arch.

3.2.2 Leaning-type arch bridge with thrust

It is assumed that the bending rigidities of arch ribs of Yufeng Bridge are cardinal number 1 and the internal forces of the main arch, main beam and leaning arch of model B under the dead loads are calculated as cardinal number 1. The internal force ratios with different bending rigidities of arch ribs can be seen in Table 6 and Fig. 13. It can be found that under the dead loads the effects of the arch rigidity on internal force ratios at bridge center in Model B are similar with that in Model A. That is, the variation of bending rigidities of arch ribs has minor effects on the axial forces at the bridge center and the moment at the main beam center. And the moments at the main arch center and the leaning arch center increase together with the bending rigidities of arch ribs. But the moments at the bridge center in Model B grow with less rates than that in Model A.

4. Parametric study on structural stability

Due to that the arch ribs of leaning-type arch bridges are primarily in compression under the dead loads, the structural stability is a significant problem during design, calculation and construction. The in-plane buckling mode and lateral buckling mode are two buckling forms of the arch bridges. For a leaning-type arch bridge, the two main arches are in vertical planes while the two leaning arches are inclined, and the transvers braces are installed between the main arch and the leaning arch on the same bridge side. Therefore, the stability of the leaning-type arch bridge is affected by various parameters, including the structural system and the inclining degree of the leaning arch.

Model A and B are still used to investigate the effect of these parameters on the linear elastic stability of leaning-type arch bridges under the dead loads. It is noted that the stiffness of the bridge deck is also included in the calculation.

As mentioned in the introduction section, Liu *et al.* (2014) obtained some analytical solutions for lateral buckling critical load of the leaning-type arch bridge based on the Ritz method. However, it is assumed that the first buckling mode of the bridge is a global outward bucking mode, which is actually not the real first buckling mode as shown in the following part. The authors realize that considering the complexity of the bridge structure, the practical way to obtain the first buckling mode of this type of bridge is through an FEM analysis.

4.1 Effects of the structural system

4.1.1 Leaning-type arch bridge without thrust

In this section, Model A is used to analyze the stability of Yufeng Bridge. The stability safety coefficient λ is 7.784. The first three buckling modes (Figs. 14-16) and the stability safety coefficients are shown in Table 7, and they are all lateral bucking modes of arches.

4.1.2 Leaning-type arch bridge with thrust

The first three buckling modes (similar to Figs. 14-16)

Table 7 First three bucking modes and the stability safety coefficients of Model A

No.	Stability safety coefficient	Buckling mode
1	7.7842	lateral asymmetrical buckling of arch ribs (mode A)
2	7.8267	lateral asymmetrical buckling of arch ribs (mode B)
3	8.8481	lateral symmetrical buckling of arch ribs

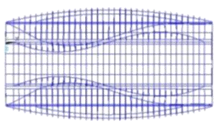


Fig. 14 lateral asymmetrical buckling of arch ribs (mode A)

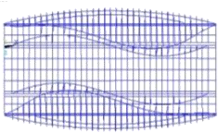


Fig. 15 lateral asymmetrical buckling of arch ribs (mode B)

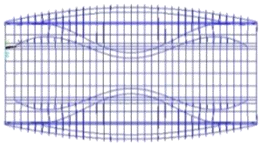


Fig. 16 lateral symmetrical buckling of arch ribs

Table 8 First three bucking modes and the stability safety coefficients of Model B

No.	Stability safety coefficient	Bucking mode
1	6.955	lateral asymmetrical buckling of arch ribs (mode A)
2	7.5241	lateral asymmetrical buckling of arch ribs (mode B)
3	8.4832	lateral symmetrical buckling mode of arch ribs

and the stability safety coefficients of Model B are shown in Table 8. In comparison with those in Model A, the first order safety coefficient of Model B decreases by 0.8. In Model A, the leaning arch is a combined bridge with the beam and the arch. But in Model B, the leaning arch is connected with substructures directly. Therefore, the decrease of the stiffness of the leaning arch in Model B leads to the decline of the stability safety coefficient. In addition, the first three buckling modes of the two models are all lateral buckling models of arch ribs. This indicates that the lateral stiffness of the leaning-type arch bridge is much less than the in-plan stiffness because there are no wind bracings between the two main arches.

4.2 Effect of angle of leaning arch

The leaning arches are inclined to improve the stability of leaning-type arch bridges. As shown in Fig. 1, the inclining angle of the leaning arches of Yufeng Bridge is 23.38°. In order to investigate the effect of inclining angle of the leaning arch on the stability of leaning-type arch bridges, Model A is used to calculate the stability safety coefficient with the inclining angle varying from 15° to 27°. It can be seen from Table 9 that the stability safety coefficient rises gradually with the increase of the inclining angle. Furthermore, with the inclining angle increasing to 27°, the buckling mode turns from lateral asymmetrical buckling mode of arch ribs to lateral symmetrical buckling mode of arch ribs.

5. Conclusions

Based on a comprehensive parametric analysis of the leaning type arch bridge under dead loads, the following conclusions and recommendations can be drawn:

• For leaning type arch bridges, the rise-to-span ratio is an important parameter that influences the internal forces both of the arches and beams. The internal forces decline obviously with the increase of rise-to-span ratio and drop most sharply with the rise-to-span ratio increasing from 1/8 to 1/7. Therefore, a rise-to span ratio below 1/7 should be avoided.

• The effects of rise-to-span ratio on the moments are more obvious than that on the axial forces at bridge center of leaning-type arch bridges. Furthermore, the internal forces at bridge center of leaning arches in the leaning-type arch bridge with thrust drop more rapidly than that in the leaning-type arch bridge without thrust.

• The bending moments at the centers of the main arches and the leaning arches are sensitive to the bending rigidities of arch ribs. However, with the bending rigidities of arch ribs increasing, the moments at bridge center in the leaning type bridge with thrust have higher growth rates than that in the leaning type bridge without thrust.

• The lateral stiffness of leaning-type arch bridge is less than the in-plan stiffness because there are no wind bracings between the two main arches. Moreover, the first three buckling modes are all lateral buckling modes of arch ribs no matter whether the structural system is with thrust or without thrust.

• Compared with the leaning-type arch bridge without thrust, the leaning-type arch bridge with thrust has a lower stability safety coefficient.

• The stability safety coefficient rises gradually with the increase of inclining angle of the leaning arch. Furthermore, with the inclining angle increasing to 27o, the buckling mode turns from a lateral asymmetrical buckling mode of arch ribs to a lateral symmetrical buckling mode of arch ribs.

It is also important to notice that these conclusions are based on a specific bridge project, so that the results would not be arbitrarily appropriate for all leaning type bridges with different span lengths or different leaning angels of the leaning arch. This problem should be studied in future work.

Table 9 Effects of inclining angle of leaning arch on the stability of leaning-type arch bridges

Inclining angle	27°	24°	21°	18°	15°
Stability safety coefficien t	8.301	8.141	6.856	6.253	5.943
Buckling mode	Lateral symmetrica l buckling mode of arch ribs (Fig. 16)	Lateral asymmetrica l buckling mode of arch ribs (Fig. 14)	Lateral asymmetrica l buckling mode of arch ribs (Fig. 14)	Lateral asymmetrica l buckling mode of arch ribs (Fig. 14)	Lateral asymmetrica l buckling mode of arch ribs (Fig. 14)

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