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Arch-to-beam rigidity analysis for V-shaped rigid frame composite arch bridges

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Abstract. We proposed the concept of nominal rigidity of a long-span V-shaped rigid frame composite arch bridge, analyzed the effects of structural parameters on nominal rigidity, and derived a theoretical nominal rigidity equation. In addition, we discussed the selection of the arch-to-beam rigidity ratio and its effect on the distribution of internal forces, and analyzed the influence of the ratio on the internal forces. We determined the delimitation value between rigid arch-flexible beam and flexible arch-rigid beam. We summarized the nominal rigidity and arch to beam rigidity ratios of existing bridges. The results show that (1) rigid arch-flexible beam and flexible arch-rigid beam can be defined by the arch-to-beam rigidity ratio; (2) nominal rigidities have no obvious differences among the continuous rigid frame composite arch bridge, V-shaped rigid frame bridge, and arch bridge, which shows that nominal rigidity can reflect the global stiffness of a structure.

Keywords: bridge engineering; V-shaped rigid frame composite arch bridge; nominal rigidity; structural parameters; arch-to-beam rigidity ratio

1. Introduction

A V-shaped rigid frame composite arch bridge is a composite structure that comprises the main-span inclined leg of a V-shaped rigid frame and connected skewback. When the V-shaped rigid frame and arch bridge structure are combined, the dead load is primarily borne by the main beam, and the second phase dead load and live load are primarily borne by the composite structure. On one hand, the main beam is similar to a rigid tie bar; the V-shaped inclined leg can balance the horizontal thrust that is transmitted from the arch and rigid frame to the foundation. The cooperative working performance of the arch rib suspenders and the inclined leg reduces the height of the main beam and the span significantly, and improves the long-term deformation and stress states of the entire composite structure. On the other hand, this type of structure balances the horizontal thrust of the skewback by adjusting the dip angle of the outside inclined leg and

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improves the stress conditions of the foundation. Furthermore, it provides a new development possibility for long-span railway bridge structures.

With the increase of the modern composite bridge' span, bridge's horizontal width is getting larger. The spatial effect of long-span V-shape rigid frame composite arch bridge is increasingly obvious as well. Therefore, the result of plane analysis cannot reflect the bridge's real force conditions properly (Ma 2011, Ribeiro 2012).

Long-span V-shape rigid frame composite arch bridge is a beam-arch combination system in which the main girder is continuous and piers are consolidated with the girder. Three-direction prestressed system is usually adopted in this kind of bridge, hense the force conditions are complex and the spatial effects are also evident. Nevertheless, it is impossible to calculate the stress conditions of V-Shape Piers. For the safety of bridge structure, it is necessary to do spatial behavior analysis (Altunisik 2010, Pan 2011) for the whole structure.

Some research results of the continuous composite arch bridges, such as the basic performance, creep and shrinkage of concrete, principle of the controlled completed bridge state, relation between structure and internal force, construction methods and cases, are also reported (Jin 2001, Li 1999).

The complicated mechanical behaviors of beam, arch and pier combination area and local stress distribution in anchorage zones of long-span continuous rigid frame composite arch bridge are further studied (Jiang *et al*. 2010, 2011).

According to the relative bending stiffness of the arch rib and rigid frame (beam), a V-shaped rigid frame composite arch bridge can be divided into three combination systems: rigid arch–flexible beam system, flexible arch–rigid beam system, and rigid arch–rigid beam system. The current research first considers the overall static displacement of girders, and then proposes the concept of nominal rigidity of long-span V-shaped rigid frame composite arch bridges, analyzes the impact of structural parameters on nominal rigidity, and finally deduces a theoretical equation of nominal rigidity. The mechanical behaviors of the V-shaped rigid frame composite arch bridge are closely related to the rigidity ratio of its components; the rigidity values of the arch and beam affects the distribution of internal forces. The rigidity ratio of the arch rib and girder of the V-shaped rigid frame composite arch bridge is the key factor that affects the mechanical behavior of the overall structure. This paper includes a discussion on the selection of the arch-to-beam rigidity ratio and the impacts on the distribution of internal forces. It also analyzes the rigidity ratio's influence on the internal forces of the structure and deduces a delimitation value of the rigid arch-flexible beam and the flexible arch-rigid beam. The conclusion provides designers with guidance on the selection of appropriate structural parameters.

The newly built Xiaolan water channel bridge, a component of the Guangzhou–Zhuhai intercity rail transportation system (Section ZH-1), has introduced V-shaped rigid frame composite systems for high-speed passenger rail systems. The Xiaolan Bridge, which is 7686.57 m long, has the longest high-speed railway bridge in the world (Gou *et al*. 2010).The main bridge is a V-shaped rigid frame combination steel-tube arch bridge with a span of 100 + 220 + 100 m; a prestressed concrete continuous rigid frame and steel-tube concrete arch bridge bear stress simultaneously. The included angle of the outside inclined leg and horizontal surface is 34.6° and a single dual-chamber box section is adopted. The box girder has a lateral width of 10 m, height of 4 m, and wall thickness of 1.5 m in the transverse direction and 1.2 m in the height direction. The septum thickness is 1.0 m. The included angle of the inside inclined leg and horizontal surface is 46.4°, and a single dual-chamber box section is adopted. The box girder has a lateral width of 13.8 m, height of 4 m, and wall thickness of 2 m in the transverse direction and 1.2 m in the height

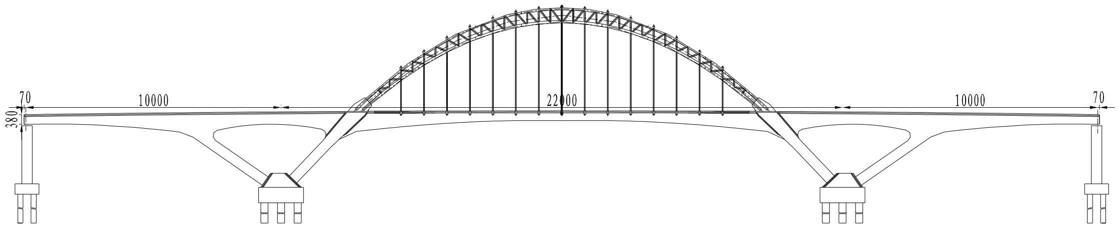

Fig. 1 Elevation of the Xiaolan Bridge (cm)

direction. The septum thickness is 1.5 m. At the fulcrum of the main beam, the beam height is 7.8 m, and at the middle of the main span and the fulcrum of side span, the beam height is 3.8 m. Inside the V-shaped rigid frame, the minimal beam height is 4.8 m. The web thicknesses of the side spans and mid-span from root to mid-span are, in order, 80, 55, and 35 cm. The girder web thickness is locally changed to 120 cm at the intersection with the inner leg in a broken-line manner. Inside the V-shaped rigid frame, the beam web thicknesses are 80 and 55 cm and vary in a broken-line manner. The thickness of the bottom plate changes from 35 cm at the mid-span to 120 cm at the root in a parabolic law by 1.8 times manner. In the V-shaped rigid frame, the bottom plate thickness of the beam varies gradually from 50 cm at the mid-span to 100 cm at the root in a circular curved manner. The bottom plate is thickened near the consolidation point of the inclined leg and girder of the V-shaped rigid frame. An elevation view of the Xiaolan Bridge is shown in Fig. 1.

2. Nominal rigidity of V-shaped rigid frame composite arch bridge and theory of arch-to-beam rigidity ratio

The three elements of structural safety are structural stiffness (ability to resist structural deformation), structural strength, and stability. Static and dynamic behaviors are related to the global structural stiffness; however, this research does not focus on dynamic characteristics. The relationship between structural displacement and rigidity is as follows

$$[K]\{\delta\} = \{P\} \tag{1}$$

where $\{P\}$ is the structural load vector, $\{\delta\}$ is the structural displacement vector under the action of $\{P\}$, and $[K]$ is the matrix of global structural stiffness.

Thus, a rationally designed structure system can meet the global stiffness of the structure and ensure structural safety.

The global structural stiffness comprises the following. (1) Physical rigidity: material elastic constants, such as Yang's modulus E and shear modulus G. (2) Section stiffness: section features of the structural members, such as sectional area A, moment of inertia I, and polar moment of inertia I_P. (3) Geometric composition rigidity: impacts of geometric composition of the structure, such as boundary conditions, length and angle of bars, and bar connections (Chen 2005).

Frequently used engineering materials are limited; therefore, it is difficult to change the physical rigidity by relying on scientific and technological progress and the study of new materials. However, it is easier to realize changes in physical rigidity by changing section rigidity and geometric composition.

The overall stiffness of a continuous rigid frame is primarily provided by girder rigidity; however, in an arch bridge, it is provided by the arch rib rigidity. If the continuous rigid frame is regarded as the starting point and the arch bridge as the terminal point, the two points constitute a straight line. Then, the V-shaped rigid frame arch bridge can be regarded as a dot on this straight line. As this dot approaches the starting point, the performance of the V-shaped rigid frame arch bridge approaches that of the continuous rigid frame. On the other hand, as the dot approaches the terminal point, the performance approaches that of the arch bridge. Therefore, the performance of the V-shaped rigid frame arch bridge varies significantly, i.e., this type of structure can be a “rigid beam–flexible arch” system or a “flexible beam–rigid arch” system. Researching the various relationships of arch rigidity and girder rigidity, as well as the overall rigidity characteristics of structures, can clarify the mechanical characteristics of the V-shaped rigid frame composite arch bridge. The V-shaped rigid frame arch bridge is a high-order hyperstatic structure; therefore, the concept of nominal rigidity is introduced to precisely express structural rigidity. The algebraic sum of vertical rigidity of the primary members of the V-shaped rigid frame composite arch bridge is defined as the nominal rigidity. The ratio of relative rigidity between the arch and beam is defined as the arch-to-beam rigidity ratio. The nominal rigidity and the arch-to-beam rigidity ratio can be used to study the structural performance in a conceptual design phase.

3. Theoretical equation of nominal rigidity for the V-shaped rigid frame composite arch bridge

The nominal rigidity of the V-shaped rigid frame composite arch bridge is the algebraic sum of the girder, tie, and arch rib rigidities. Under vertical loads, the vertical deflection of the bridge consists of girder deflection, displacement induced by elastic deformation of suspenders, and vertical deflection caused by skewback displacement. The vertical displacement of girders and suspenders, as well as the bending rigidity of the arch rib under unit load, are deduced as follows.

(1) Maximal girder deflection under unit vertical load by structural mechanics

$$\delta_{G\max} = \frac{L_G^3}{mE_G I_G} \tag{2}$$

where E_G is the girder elastic modulus, I_G is the sectional inertia moment, L_G is the span, and m is the parameter determined by girder boundary conditions.

(2) Maximal vertical displacement of suspenders subject to tension under unit vertical loads

$$\delta_S = \frac{H_S}{E_S A_S} \tag{3}$$

where E_S is the suspender elastic modulus, A_S is the sectional area, and H_S is the length.

(3) Skewback displacements include horizontal displacement, vertical displacement (settlement), and rotation (angular change). Each type of displacement causes internal forces in the arch, and relative angular change of skewback causes both horizontal and vertical displacements. These values are closely related to rib bending rigidity.

$$K_A = k\frac{E_A I_A}{f^2 L_A} \tag{4}$$

where E_A is the elastic modulus of rib, I_A is the sectional inertia moment, f is the calculated vector height, L_A is the calculated span length, and K is a parameter determined by boundary conditions.

Based on the above discussions, the nominal rigidity equation of the V-shaped rigid frame composite arch bridge is as follows

$$\gamma = \frac{1}{\delta_G} + \frac{1}{\delta_S} + K_A = m\frac{E_G I_G}{L_G^{\ 3}} + \frac{E_S A_S}{H_S} + k\frac{E_A I_A}{f^2 L_A} \tag{5}$$

The arch-to-beam rigidity ratio can be expressed as follows

$$\lambda = E_A I_A / E_G I_G \tag{6}$$

4. Nominal rigidity and arch-to-beam rigidity ratio of the V-shaped rigid frame composite arch bridge

4.1 Impact of structural parameters on nominal rigidity

For the V-shaped rigid frame composite arch bridge with a given span, the nominal rigidity is mainly determined by three independent parameters: bending rigidity of the arch rib $E_A I_A$, bending rigidity of the girder $E_G I_G$, and axial rigidity of the suspenders $E_S A_S$. For a given span, these parameters are the primary structural parameters of the V-shaped rigid frame composite arch bridge. Thus, the overall mechanical characteristics of this system can be reflected by the concept of nominal rigidity.

The effect of these parameters on structural rigidity can be discussed in relation to Eq. (5).

(1) Arch rib bending inertia moment
The bending rigidity of an arch rib $E_A I_A$ increases with flexural inertia moment I_A. When the third item of Equation (5) increases, the nominal rigidity γ increases; however, the mid-span deflection decreases. Many “flexible beam–rigid arch” bridges are of this type. Among existing bridges, a triangle rigid frame steel truss arch combination system is adopted in the main section of the Guangzhou-Xinguang Bridge.

(2) Girder bending inertia moment
The girder bending rigidity $E_G I_G$ increases with bending inertia moment I_G. When the first item of Eq. (5) increases, the nominal rigidity γ increases; however, the mid-span deflection decreases. This type of bridge is also common; a “flexible arch-rigid beam” system is an example of this type. Among existing bridges, a prestressed concrete continuous rigid frame flexible steel tube arch bridge is adopted as the main section of the Yichang Bridge of the newly built Yichang-Wanzhou railway, a prestressed concrete V-shaped continuous rigid frame steel tube arch composite system is adopted in the Xiaolan Bridge of the Guangzhou-Zhuhai intercity rapid rail transit system, and a Y-shaped rigid frame steel box basket-handling arch system is adopted as the main section of the Caiyuanba Yangtze River Bridge in Chongqing.

(3) Suspender sectional area
It is easy to determine that axial rigidity $E_S A_S$ increases with suspender area A_S. When the second item of Equation (5) increases, the nominal rigidity γ increases; however, the mid-span deflection decreases. Therefore, the nominal rigidity of the entire structure increases with arch rib, girder, and suspender rigidities. Three methods can be used to decrease the mid-span deflection of the V-shaped rigid frame composite arch system, i.e., to increase nominal rigidity γ: increasing the bending rigidity of the arch rib, increasing the bending rigidity of the girder, and increasing the suspender sectional area.

4.2 Impact of arch-to-beam rigidity ratio on the structure's internal force

The mechanical behaviors of the rigid frame arch composite system are closely related to the rigidity ratio of its components. Arch, beam, and suspender rigidity values affect the distribution of internal force. Appropriate arch-to-beam rigidity ratio values result in uniformly distributed stress in the structure, allow easy handling of the steel bar structure, and allow for a symmetric structural appearance (Liu 2006). The arch-rib-to-girder rigidity ratio of the V-shaped rigid frame arch composite system is the key factor that affects the overall mechanical behaviors of the structure. The arch-to-beam rigidity ratio affects the distribution of structural bending moment. In general, the arch rib bending moment is reduced as much as possible because it is a compression member. High arch-to-beam rigidity ratio values should be avoided. On the other hand, it is not economical if the girder bending moment is significantly large. From the above analysis, the bending moment ratio of girder to arch rib differs significantly when the arch-to-beam rigidity ratio is either low or high, which increases the material usage and causes uneven loading on the structure.

Consider a V-shaped rigid frame arch system with a span of 100 + 220 + 100 m. Keep the arch and beam sectional area constant and vary the bending rigidity ratio of the arch rib to tie beam. Then analyze the changes in internal forces. To create equivalent comparison conditions in the analysis, the spatial finite element analysis is conducted on the basis of arch-to-beam rigidity ratios of 1/20, 1/15, 1/5, 1, 5, 15, and 20. The mid-span axial force and the bending moment of the girder and arch can be calculated under dead and live loads with different bending rigidity ratios. Taking the structure's internal forces with an arch-to-beam bending rigidity ratio of 1 as reference, calculate the ratio of other internal forces (I_{arch} / I_{girder} = 1/20, 1/15, 1/5, 1, 5, 15, and 20) to the reference value (I_{arch} / I_{girder} = 1). Take I_{arch} / I_{girder} as the *x*-coordinate and internal force ratios as the y-coordinate, and then draw the variation trend curve of the axial force and bending moment of the arch and beam under dead and live loads relative to changing rigidity, as shown in Figs. 2-5.

Figs. 2-5 show that, under dead loads and with constant sectional arch and beam area, the increase in arch-to-beam rigidity ratio has less impact on the axial force of the V-shaped rigid frame flexible arch composite system. The axial force of the girder increases slightly, and that of the arch decreases slightly. The main effect of arch-to-beam rigidity ratio on this type of bridge is the distribution of arch and beam structural bending moment. However, under live loads, increased arch-to-beam rigidity ratio affects the V-shaped rigid arch composite system differently; arch and beam axial forces tend to decrease in a narrow range. The bending moment of the structure is borne by arch and beam components and is distributed according to rigidity ratio. However, change in rigidity ratio has a more significant impact on the arch rib bending moment than that of the girder. Thus, as arch and girder axial forces decrease, most of the bending moment transfers from the girder to the arch rib with increasing rigidity in the arch rib.

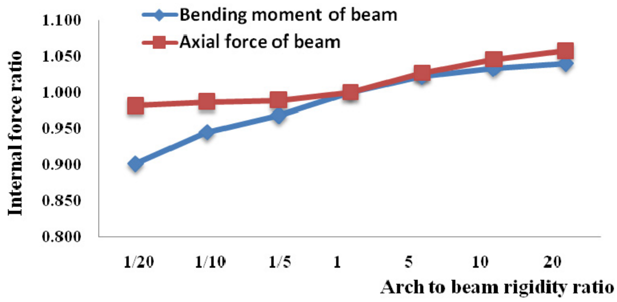

Fig. 2 Internal force ratio diagram for a girder under dead load based on different arch-to-beam rigidity ratios

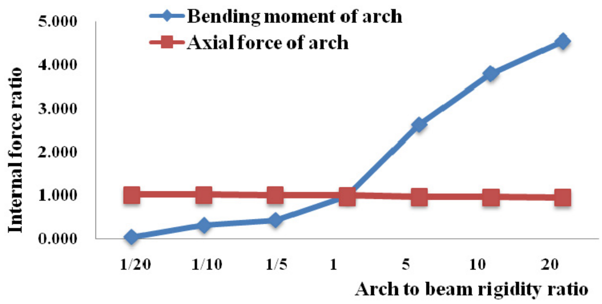

Fig. 3 Internal force ratio diagram for an arch rib under dead load based on different arch-to-beam rigidity ratios

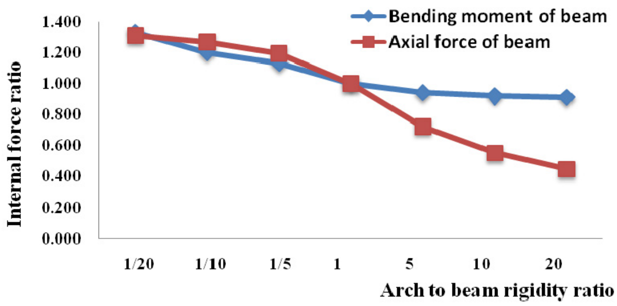

Fig. 4 Internal force ratio diagram for a girder under live loads based on different arch-to-beam rigidity ratios

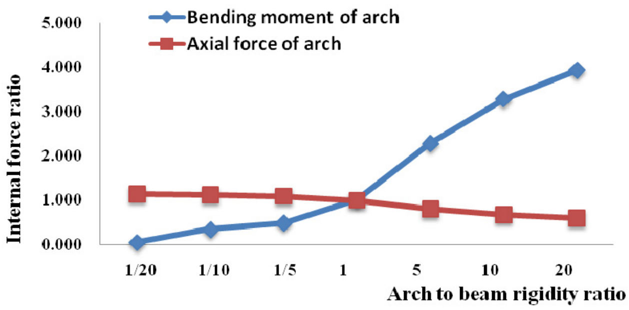

Fig. 5 Internal force ratio diagram for an arch rib under live loads based on different arch-to-beam rigidity ratios

The rigidity of the V-shaped pier is also an important factor affecting the distribution of the internal forces of the structure. The V-shaped support greatly increases the rigidity of the beam near the fulcrum, which reduces the bridge span and the deflection of structure. In addition, the horizontal rigidity of the bridge increases and the pier height decreases due to the presence of the V-shaped support.

4.3 Delimitation of rigid arch-flexible beam and flexible arch-rigid beam systems

According to the relative bending rigidity of the arch rib and rigid frame (beam), V-shaped rigid frame arch composite systems are classified as a rigid arch–flexible beam system, a flexible arch–rigid beam system, and a rigid arch-rigid beam system. Refer to literatures about arch and beam composite systems for the delimitation value of the arch-to-beam rigidity ratio in rigid frame arch composite systems.

For the delimitation value of the arch-to-beam rigidity ratio of these systems, Jin (2001) states that when the arch-to-beam rigidity ratio $E_A I_A / E_G I_G \geq 10$, the beam rigidity can be ignored, and the bending moment is borne by the arch independently. Such a bridge is referred to as a tied arch. When $E_A I_A / E_G I_G \geq 1/10$, the rigidity of the arch can be ignored and the bending moment is borne by the beam independently. Such a bridge is referred to as a Langer arch.

Article 5.2.12 in the Fundamental Code for Design on Railway Bridge and Culvert (TB10002.1-2005) specifies that, in a tied bar arch bridge structure, the arch rib is regarded as flexible, only bearing axial pressure if the arch-rib-to-tied-girder rigidity ratio is less than 1 / 80-1 / 100. However, if the arch-rib-to-tied-girder rigidity ratio is greater than 80-100, the tie girder is regarded as a tied bar that only bears axial tension, and the beam and arch should be hinged.

In accordance with the two documents mentioned above, a previously reported study also specifies that the definitions of the rigid arch-flexible beam and flexible arch-rigid beam are based on the fact that the arch rib or girder only bears the axial force rather than bending moment (Yi 2007). In addition, the study takes statically indeterminate internal forces of both the rigid arch-flexible beam and flexible arch-rigid beam as the axial forces of the girder, and then calculates other internal forces and displacements.

Structure calculation involves both internal forces and displacements; thus, the condition for defining a rigid arch–flexible beam and a flexible arch–rigid beam is that internal forces and displacements in an actual structure and a simplified model are mostly the same. According to another study (Gou 2010) the rigid arch–flexible beam should have the following characteristics: axial force of the girder is stable, bending moment of the arch rib is essentially unchanged, and deflection of the arch rib is stable. The flexible arch-rigid beam should have the following characteristics: axial force, bending moment, and deflection of the girder are essentially unchanged. Thus, a standard rule to define the rigid arch-flexible beam and the flexible arch–rigid beam is that the axial force of the girder, bending moment of the arch rib and girder, and deflection of the arch rib and girder are essentially unchanged after simplification.

The Fundamental Code for Design on Railway Bridge and Culvert (TB10002.1-2005) does not convert the arch and beam composite system, in which the rigidity of the arch rib is much less than that of the girder, to a system with no arch rib bending rigidity; such a system is simplified to a Langer arch. No bending rigidity of a continuous linear arch rib means infinite “hinges”. However, in the Langer arch, limited “hinges” realizes zero-bending rigidity. Therefore, the Langer arch with a limited number of “hinges” is not equal to a continuous linear arch and beam composite system with no bending rigidity. Therefore, $E_A I_A / E_G I_G \leq 1/20$ is selected to define a flexible arch–rigid

Table 1 Nominal rigidity and arch-to-beam rigidity ratio statistics

Type	Bridge name	Structure system	Span arrangement /m	Nominal rigidity /N/m	Arch-to-beam rigidity ratio
Continuous rigid frame composite arch bridge	ChongQing Cai Yuanba ChangJiang River Bridge	Y-shaped rigid frame steel box basket-handling arch combination system	102 + 420 + 102	1.24e8	0.003
	Guang Zhou Xinguang Bridge	Triangle rigid frame steel girder arch combination system	177 + 428 + 177	1.55e7	20.985
	YiChang ChangJiang River Bridge	Continuous rigid frame flexible steel tube arch combination system	130 + 2 × 275 + 130	6.01e7	0.064
	XiaoLan ShuiDao Large Bridge	V-shaped continuous rigid frame steel tube arch combination system	100 + 220 + 100	6.50e7	0.048
V-shaped rigid frame bridge	Qiao Daohu Bridge main span	Prestressed concrete long porous V-shaped pier continuous rigid frame	70 + 7 × 10 + 70 + 40	6.13e7	/
	JiangXi Tower Bridge	Prestressed concrete V-shaped pier continuous rigid frame	45 + 70 + 45	1.56e8	/
	DongYang River Bridge	Prestressed concrete V-shaped pier continuous rigid frame	50 + 75 + 50	1.76e8	/
	QingTian Tower Mountain Bridge main span	Prestressed reinforced V-shaped pier continuous rigid frame	80 + 120 + 80	2.15e7	/
Arch bridge	Qian Daohu No.1 Super Large Bridge	Deck-type concrete-filled steel-tube truss arch bridge	254.8	2.69e7	/
	ChunAn NanPu Bridge	Half-through concrete-filled steel-tube truss arch bridge	330	1.96e7	/
	NaMo Bridge	Half-through concrete-filled steel-tube truss rid arch bridge	190	2.60e7	/
	ShiJia DuLi River Bridge	Half-through concrete-filled steel-tube truss arch bridge	176.8	2.90e7	/

beam. With the exception of some relatively large errors caused by side suspender forces and skewback moments, errors resulting from displacement of internal forces were sufficiently small. On the other hand, $E_A I_A$ / $E_G I_G \geq 20$ is selected to define a rigid arch-flexible beam. The delimitation value given by the Fundamental Code for Design on Railway Bridge and Culvert (TB10002.1-2005) is a little severe.

4.4 Nominal rigidity and arch-to-beam rigidity ratio statistics for existing bridges

According to the design data of existing domestic continuous rigid frame composite arch bridges, V-shaped rigid frame bridges, and arch bridges, nominal rigidity and arch-to-beam rigidity ratio statistics are listed in Table 1.

The following conclusions can be made based on the above information (Table 1):

(1) The nominal rigidity of the continuous rigid frame composite arch bridge lies between 1.55e7 and 1.24e8. For the V-shaped rigid frame bridge, the value is between 2.15e7 and 1.76e8. For the arch bridge, the value ranges between 1.96e7 and 2.90e7. There are no significant differences among them.

(2) The arch-to-beam rigidity ratio of the continuous rigid frame flexible arch lies between 0.003 and 0.048 and accords with the delimitation value of the flexible arch-rigid beam. The Guangzhou-Xinguang Bridge is a continuous rigid frame-rigid arch, and its rigidity ratio is 20.985, which completely accords with the delimitation value of the rigid arch–flexible beam. Thus, the delimitation value of the flexible arch-rigid beam can be taken as $E_AI_A / E_GI_G \leq 1/20$, and that of the rigid arch–flexible beam can be taken as $E_AI_A / E_GI_G \geq 20$.

The following conclusions can be drawn from the above comparisons: the arch-to-beam rigidity ratio can delimit a rigid arch–flexible beam and a flexible arch–rigid beam; there are no obvious differences in nominal rigidity among the continuous rigid frame composite arch bridge, V-shaped rigid frame bridge, and arch bridge, which indicates that the nominal rigidity can reflect the integral rigidity of a structure.

5. Conclusions

This paper primarily examines the vertical static stiffness of an arch and beam of a V-shaped rigid frame composite arch bridge. The results indicate the following:

(1) The nominal rigidity of the entire structure increases with arch rib, girder, and suspender rigidities. Three methods can be employed to decrease the mid-span deflection of the V-shaped rigid frame composite arch system, i.e., to increase nominal rigidity γ: increasing the bending rigidity of the arch rib, increasing the bending rigidity of the girder, and increasing the area of the suspender section. In comparison with data of constructed bridges, there are no obvious differences in the nominal rigidity among continuous rigid frame composite arch bridges, V-shaped rigid frame bridges, and arch bridge, which indicates that nominal rigidity can reflect integral rigidity of a structure.

(2) An increase of the arch-to-beam rigidity ratio has little impact on the axial force of the V-shaped rigid frame flexible arch composite bridge under dead loads. The main impact is on the distribution of the structural bending moment of the arch and beam. Increasing the arch-to-beam rigidity ratio allows the bending moment of the arch and beam to increase gradually at first, and then rapidly. The bending moment of the girder increases slightly

and is influenced much less than that of the arch rib.

Under live loads, the impact on the axial force of the V-shaped rigid-framed flexible arch composite bridge is different from that for dead loads with increased rigidity ratio. The axial forces of the arch and beam decrease slightly. The bending moment of the structure is borne by the arch and beam and is distributed according to the rigidity ratio. However, a change in the rigidity ratio has more significant impact on the bending moment of the arch rib than that of the girder. Thus, most of the bending moment transfers from the girder to the arch rib with increasing rigidity in the arch rib.

In addition, the rigidity of a V-shaped pier is an important factor affecting the distribution of internal forces of a structure. The V-shaped support greatly increases the rigidity of the beam near the fulcrum and consequently reduces the span of the bridge and deflection of the structure. Simultaneously, the horizontal rigidity of the bridge increases and height of the pier height decreases due to the V-shaped support.

(3) With regard to the delimitation value of the rigidity ratio of a rigid frame composite arch system, the delimitation value of a flexible arch-rigid beam can be taken as $E_A I_A / E_G I_G \leq 1/20$, and that of a rigid arch-flexible beam can be taken as $E_A I_A / E_G I_G \geq 20$ by referring to guidelines for beam and arch composite systems and data for existing domestic continuous rigid frame composite arch systems.

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