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Strength Optimisation and Static Performance Analysis of Arch Ribs of Steel-tube Concrete Arch Bridge

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Abstract: By means of finite element simulation, the axial compressive stiffness of different steel-tube concrete short columns was imported into the finite element model, and the effects of adopting new steel-tube concrete arch ribs on the mechanical properties of the key components of steel-tube concrete arch bridges, such as internal forces and displacements, were analyzed. The results show that: with the increase of the axial compressive stiffness of the arch rib chord, under different load combinations, the vertical displacement of the arch rib chord will increase, and the structure will be lifted up, with a maximum of 31.85%; the vertical displacement of the deck slab will also increase, with a maximum increase of 6.8%, which is smaller than the vertical displacement of the arch rib chord; the absolute value of the downward and transverse displacements of the arch rib chord will be reduced, with a maximum reduction of 7.1% respectively. The absolute values of the transverse and crossover displacements of the arch rib chord tube will be reduced, with the maximum reduction of 7.1% and 6.8%, respectively. In the project of arch bridge, the deflection and deformation of the arch rib, deck plate and other components of the more stringent restrictions, especially the vertical displacement, it is recommended to use the higher axial compressive stiffness of the steel pipe concrete arch rib.

Keywords: Steel-tube Concrete; Axial Stiffness; Steel-tube Concrete Arch Bridge; Static Performance.

1. Introduction

Arch bridge is one of the commonly used bridge types for large-span bridges, which is competitive in the range of tens to hundreds of metres span. Due to the special force characteristics of arch bridges, in mountainous areas and other areas with good geological conditions, thrust arch bridges are even more competitive bridge types; in plains and areas with poor geological conditions, they can also be designed as non-thrust tie arch bridges[1]. As the arch bridge span increases and the section pressure increases, the requirements for materials and structure become more and more stringent[2]. Steel pipe concrete arch bridge arch ribs, columns and other components are used in steel pipe concrete structure with high bearing capacity, as one of the breakthroughs in the structural application of arch bridges[3], compared with other bridge structural forms, there is a significant advantage in the stress performance[4][5][6], economic benefits and other aspects.

Steel pipe concrete structure makes the core concrete in a three-way stress state, which improves the structural strength and ductility properties of concrete, and enhances the stability of the overall structure[8][9][10][11], while solving the arch bridge material high strengthening and arch construction lightweight problems[2], in addition, the steel pipe concrete arch bridge also has a beautiful structural form, the stress characteristics of a clear, give full play to the characteristics of the material and other advantages[9]. Therefore, steel pipe concrete arch bridges have been rapidly developed all over the world[7][12][13][14][15][16][17].

The research around steel pipe concrete arch bridges mainly focuses on the five aspects of hollow steel pipe concrete arch ribs[18], arch axis line shape[19], arch axis coefficients, arch rib girder heights, transverse coupling arrangement, column arrangement[20], hollow steel pipe concrete hollow ratio and wall thickness of steel pipe section[21], transverse bracing structural forms and their stiffnesses[22], the comprehensive cost of arch ribs[23], the sagittal-span ratio[24], and the arch rib isotropic cross-section optimization analysis[25], etc., there are fewer studies on arch bridges with different new steel-tube concrete structures. At present, the research on new steel pipe concrete structures is quite abundant, and steel pipe concrete structures have been innovated with different and composite types of steel pipe concrete, such as hollow steel pipe concrete with embedded hollow steel pipe, square steel pipe concrete with externally embedded square steel pipe, internally embedded square steel pipe concrete with embedded hollow steel pipe, and section steel-steel concrete with embedded steel sections, and so on. Due to the lack of in-depth research and relevant design specifications, these new types of steel pipe concrete structures are rarely used in steel pipe concrete arch bridges. Therefore, it is necessary to combine the steel pipe concrete arch bridge and the new steel pipe concrete structure to study the influence of the new steel pipe concrete structure on the mechanical properties of the steel pipe concrete arch bridge, and to make a groundbreaking work for its wide application.

2. Research Background

The arch bridge adopts top-bearing steel-tube concrete variable truss arch with calculated span of 220m, with four-tube trusses for each arch rib, the arch axis adopts the suspension chain line, the arch axis coefficient m=1.28, the sagittal height h=44m, the sagittal-span ratio f=1/5, and the arch ribs of the main bridge adopts the cemented system with the foundation.

The upper and lower chords of the arch ribs are made of φ 900×26mm straight-seam welded pipes, which are filled with C55 self-compacting micro-expansive concrete, the vertical web at the columns, the vertical web and diagonal web at the first section are made of φ426×16mm steel pipes, the rest of the vertical web and diagonal web are made of φ426×12mm steel pipes, and the upper and lower flat joints of the arch ribs are made of φ500×16mm steel pipes. A total of 26 "K" braces are set up for the left and right bays of the bridge, and 8 "I" cross braces are set up for the foot of the arch. Horizontal chords of transverse braces are made of φ500×12mm steel pipes, and vertical webs and diagonal bars are made of φ400 ×12mm steel pipes.

There are 26 columns on the arch, filled with C55 self-compacting micro-expansion concrete, and the distance between columns on each side is 16.8 m. The columns are made of φ426×12mm steel pipe, and the cross link is made of φ245×10mm steel pipe. The steel tubes used for the whole bridge are all Q345 strength steel.

The deck system of the main bridge adopts steel-mixed combination beams with a span of 16.8m, and six longitudinal girders are erected along the transverse direction of the arch bridge above the cap beams. The steel longitudinal girders have a beam height of 1.2m and a transverse spacing of 2.45m, and a steel transverse girder is set up every 5.61m or 5.58m along the bridge with a beam height of 0.8m; the steel longitudinal and transverse girders are all welded I-beam cross-section. The bridge deck is made of 12cm thick ordinary reinforced concrete precast panels, the top surface is made of 9cm thick monolithic cast-in-place CF50 steel fibre concrete layer, and the bridge deck is paved with 10cm thick asphalt concrete layer.

3. Axial Compression Test of Short Steel-tube Concrete Columns

3.1. Experimental Design

Three structural forms and four concrete strength grades were set up around the structural form and core concrete strength grade of short steel pipe concrete columns, and orthogonal tests were carried out with structural forms and concrete strength grades, and a total of 12 sets of short steel pipe concrete column specimens were cast.

(a) metal bellow (b) Reinforced Metal Bellow

Figure 1. Main components of short steel-tube concrete columns

The exploration of the structural form of the short steel pipe concrete column includes three types of specimens: i.e., a short ordinary steel pipe concrete column, made by pouring concrete into the steel pipe; a short compound steel pipe concrete column embedded with stainless steel bellows under the condition of keeping the steel content constant, which is made by adding metal bellows into the steel pipe and then pouring concrete; and a short reinforced steel pipe concrete column embedded with stainless steel bellows followed by the addition of annular hoops and radial reinforcement, which is made by adding metal bellows welded with radial hoops and annular reinforcement and then pouring concrete into the steel pipe, as shown in Fig. 1.

Arch bridge arch rib chord pipe OD 900mm, wall thickness of 26mm straight seam steel pipe, chord pipe cross-section steel content of 12.6%. As a reference, the test in the outsourcing of steel pipe selection of 159mm OD seamless steel pipe, length of 477mm, the maximum wall thickness of 5.0mm, steel concrete short column section steel content of 13.9%; the minimum wall thickness of 4.5mm, the cross-section of the steel content of 12.4%. The bellows is made of stainless steel corrugated pipe made of SUS304 stainless steel, with an inner diameter of 80mm and an outer diameter of 110mm, and the number of corrugations per metre is 42. When the outer diameter of 159mm, wall thickness of 4.5mm seamless steel pipe and stainless steel bellows nested together, the cross-section steel content of the same 13.9%. These three structural forms of short steel pipe concrete columns can be compared with the mechanical properties of ordinary short steel pipe concrete columns and compound steel pipe concrete with the same steel content, and the mechanical properties of short reinforced steel pipe concrete columns with the addition of a combination of annular hoops and radial reinforcement on the basis of compound steel pipe concrete.

The arch bridge arch rib filler concrete is made of C55 strength grade self-compacting micro-expansive concrete, which is used as a reference to gradually increase the strength grade of the core concrete, thus the exploration of the strength grade of the core concrete of the short steel pipe concrete columns includes four levels, i.e., C55, C60, C80, and C100. the specimens are specifically designed as shown in Table 1.

Table 1. Specimen design parameters

Specimen number	Pipe Wall Thickness / Bellows Wall Thickness T/t (mm)	Core concrete strength class
P-1	5.0/0	C55
P-2		C60
P-3		C80
P-4		C100
F-1	4.5/0.8	C55
F-2		C60
F-3		C80
F-4		C100
Z-1	4.5/0.8	C55
Z-2		C60
Z-3		C80
Z-4		C100

(Note: Group P is ordinary steel pipe concrete short column specimens, Group F is compound steel pipe concrete short column specimens, and Group Z is enhanced compound steel pipe concrete short column specimens.)

3.2. Experimental Results

After the steel pipe concrete specimens reached the age of 28 days in the standard curing room, the axial compression test of steel pipe concrete short columns was carried out. The measured axial compressive stiffness is shown in Table 2, which indicates that: under the premise of the same structural form, the nominal modulus of elasticity of the steel pipe concrete short column specimens increases sequentially with the increase of the strength grade of the core concrete; under the premise of the same strength grade of the core concrete, the nominal modulus of elasticity of the steel pipe concrete short column specimens increases sequentially with the incorporation of metal bellows, as well as radial tension reinforcement and annular hoops; the increase of the strength grade of the core concrete, metal bellows, as well as radial tension reinforcement and annular hoops can all be improved. The axial compressive stiffness of steel pipe concrete short column specimens can be improved by increasing the core concrete strength grade, the addition of metal bellows and radial and circumferential reinforcement.

Table 2. Nominal modulus of elasticity of the specimen

Specimen number	Nominal modulus of elasticity (MPa)
P-1	46721
P-2	47382
P-3	49751
P-4	52370
F-1	47352
F-2	48251
F-3	50542
F-4	52952
Z-1	47743
Z-2	48682
Z-3	50892
Z-4	53223

4. Finite Element Modelling

This study focuses on compound steel pipe concrete structures and reinforced steel pipe concrete structures with strengthened restraining effect on the core concrete. Mechanical property parameters such as nominal modulus of elasticity of compound steel pipe concrete and reinforced steel pipe concrete short columns are collected, and in the Finite Element Software Madas Civil 2020, the Unified Theoretical Model is referred to as a way to simulate the steel pipe concrete arches by defining a new unitary material by referring to the Unified Theoretical Model. concrete arch ribs. This simulation method takes into account the unique constraint effects of steel pipe concrete structures, which cannot be simulated by the finite element software Madas Civil, in the way of the mechanical properties of the unity material, and analyses the influence of different types of steel pipe concrete structures on the static performance of arch bridges.

4.1. Modelling Process

The model takes the highest point of the left edge of the right chord tube on the right side of the arch rib of the right girder as the coordinate origin, the X-axis in the cis-bridge direction, the Y-axis in the transverse direction and the Z-axis in the vertical direction. There are 4,355 discrete girder units and 210 slab units in the whole bridge. The steel pipe concrete arch ribs are simulated by girder units with solid web circular cross section, the ordinary hollow steel pipe structures such as flat joints, webs and transverse braces are simulated by girder units with tubular cross section, the steel pipe concrete structures such as columns and diagonal braces at the foot of the arches are simulated by girder units with combined section, the steel longitudinal and transverse beams of the deck slabs are simulated by girder units with I-beam cross section, the steel cap girders are simulated by girder units with ribs in the box shape, and the deck plates are simulated by plate units. The specific parameter values of the materials used in each unit of the model are shown in Table 3.

Table 3. Value of each material parameter

Name of material	modulus of elasticity (GPa)	Poisson's ratio	Coefficient of linear expansion (1/C°)	Capacity (N/m^3)
Q345	206	0.3	1.2×10^{-5}	76980
C50	345	0.2	1.0×10^{-5}	25000
P-1 arch rib	46.721	0.3	1.2×10^{-5}	32220
P-2 arch rib	47.382	0.3	1.2×10^{-5}	32220
P-3 arch rib	49.751	0.3	1.2×10^{-5}	32220
P-4 arch rib	52.370	0.3	1.2×10^{-5}	32220
F-1 arch rib	47.352	0.3	1.2×10^{-5}	32220
F-2 arch rib	48.251	0.3	1.2×10^{-5}	32220
F-3 arch rib	50.542	0.3	1.2×10^{-5}	32220
F-4 arch rib	52.952	0.3	1.2×10^{-5}	32220
Z-1 arch rib	47.743	0.3	1.2×10^{-5}	32220
Z-2 arch rib	48.682	0.3	1.2×10^{-5}	32220
Z-3 arch rib	50.892	0.3	1.2×10^{-5}	32220
Z-4 arch rib	53.223	0.3	1.2×10^{-5}	32220

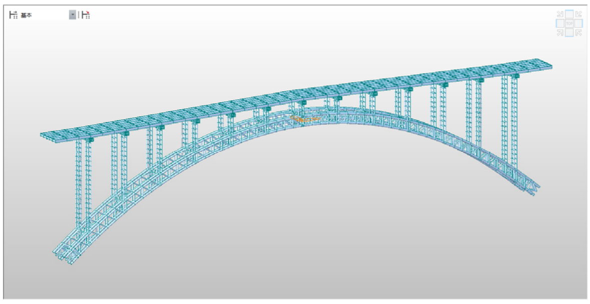
Figure 2. Main components of short steel-tube concrete columns

The main arch ribs and diagonal web at the foot of the arch bridge are rigidly connected, restraining all the degrees of freedom of the nodes; the longitudinal girders at the side spans of the bridge deck system are connected with the junction piers, relaxing the degrees of freedom of rotation around the Y-axis, and the rest of the degrees of freedom are all restrained; the longitudinal and transverse girders of the bridge deck system and the hat girders' bearings are selected to be elastically connected, and the translation stiffness in the X-direction is set to 10000kN/mm, and that of the Y- and Z-directions is set to 0.01kN /mm; between the column and the cap beam choose the fixed option in the elastic connection. An oblique view of the finite element model of the bridge is shown in Figure 2.

4.2. Load Equivalence and Combination of Actions

4.2.1. Load Equivalence

The values of permanent action are all taken according to the material's own capacity, as shown in Table 3.

Overall warming/cooling: The temperature difference of the system is determined according to the local average maximum and minimum air temperature, and the closing temperature is taken as 15℃, and the system warming is taken as 25℃ and the system cooling is taken as -25℃ after comprehensive consideration.

Transverse wind load: Considering the wind load involved in the combination of car load, taking the wind speed at the height of the bridge deck as 25m/s, according to the specification [26] for the calculation of transverse gust wind load, the arch ribs are subjected to a transverse wind load of 0.8kN/m, and the columns are subjected to a transverse wind load of 0.2kN/m.

Vehicle load: the structural safety level is highway|, according to the unidirectional three-lane calculation, choose the Chinese specification, choose 3 medium-loaded lanes and 3 partial-loaded lanes, the vehicle load is selected as shown in the figure, Pk is taken as 360kN, qk is taken as 10.5kN/m, as shown in Figure 3.

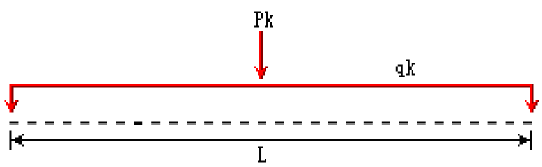

Figure 3. Vehicle Load Schematic

Vehicle braking force: braking force is calculated in the same direction according to three lanes, and the braking force of each lane is 10% of the total gravity calculated on the loading length for the standard value of lane loading, and the braking force of the three lanes is 2.34 times that of one lane, which is taken to be 0.5kN/m, and is respectively loaded on six longitudinal beams.

4.2.2. Combination of Actions

In this study, the limit state of load carrying capacity [27] with larger values of combined loads is selected for the static performance analysis of arch bridges, and the most unfavorable combination of each load action is carried out. The individual load combinations are shown in Table 4.

Table 4. Load combination

Load combination name	Load condition combinations
constant load	1.1 gravity+1.1 secondary loads +1.1 Concrete shrinkage allowable
Combination 1	1.2 constant load +1.54 vehicle load +1.155 vehicle braking force
Combination 2	1.0 Combination 1+1.155 warming loads
Combination 3	1.0 Combination 1+1.155 cooling loads
Combination 4	1.0（Combination 1~ 3）(envelope)+0.9075wind

5. Finite Element Result Analysis

The role of the role of combination 4 is considered more comprehensive, space limitations, here only in the combination of 4 under the action of the displacement of the more prominent members of the comparative analysis.

5.1. Vertical Bridge Displacement Analysis of Arch Rib Chord Tubes

Under the action of Combination 4, the maximum and minimum vertical displacement of the arch ribs in the left and right bays of the arch bridge were both in the inner chord of the upper chord of the right bay. According to the images, it can be concluded that: in each group of specimens, with the increase of the strength grade of the core concrete, the embedding of stainless steel bellows and the addition of the combination of the hoop reinforcement and the tensile reinforcement, the vertical displacement of the chord pipe of the arch ribs increased gradually, and the structure appeared to be lifted, which indicated that the increase of the modulus of elasticity, i.e., the stiffness of the chord pipe of the arch ribs increased. This shows that the increase of elastic modulus, i.e. the increase of stiffness of arch rib chord tube, the displacement of arch bridge structure was lifted accordingly, and the two comparisons increased by 31.85% and 6.1%, respectively.

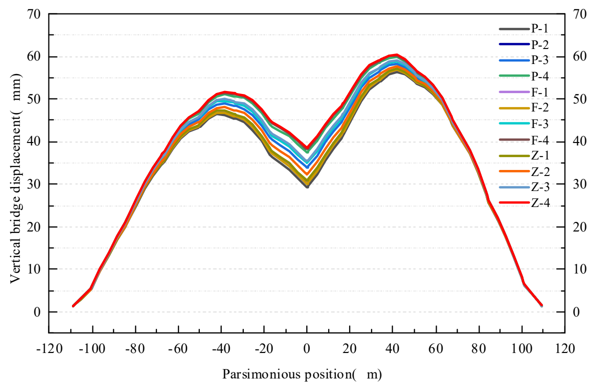

Figure 4. Maximum vertical bridge displacement of arch rib chord tube

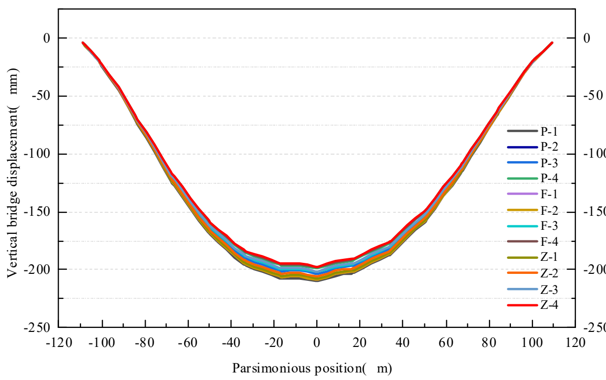

Figure 5. Minimum vertical bridge displacement of arch rib chord tube

5.2. Displacement Analysis of Arch Rib Chord Tubes in the Trans Bridge Direction

Under the action of combination 4, according to Figs. 6 and 7, it can be concluded that in each group of specimens, with the increase of core concrete strength grade, the embedding of stainless steel bellows and the addition of the combination of hoop reinforcement and tension reinforcement, the absolute value of the paraxial displacement of the arch rib chord pipe gradually decreases, which indicates that the improvement of the elastic modulus, i.e., the increase of the stiffness of the arch rib chord pipe, the paraxial displacement of the arch bridge structure will be reduced, and the two comparisons of the decrease is 7.1%, 6.8% and 6.8%, respectively. The two comparisons were 7.1% and 6.8% respectively.

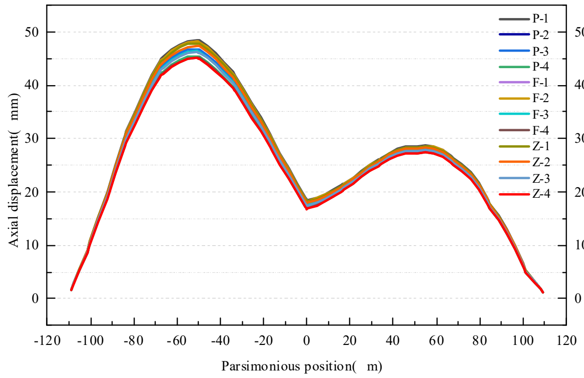

Figure 6. Analysis of Maximum Parabridging Displacement of Arch Rib String Tube

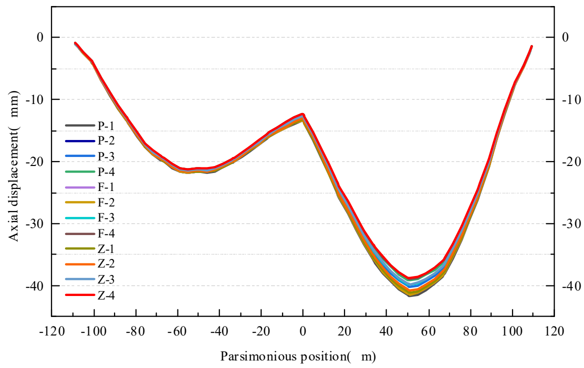

Figure 7. Analysis of Minimum Parabridging Displacement of Arch Rib String Tube

5.3. Analysis of Transverse Bridging Displacements of Arch Rib Chord Tubes

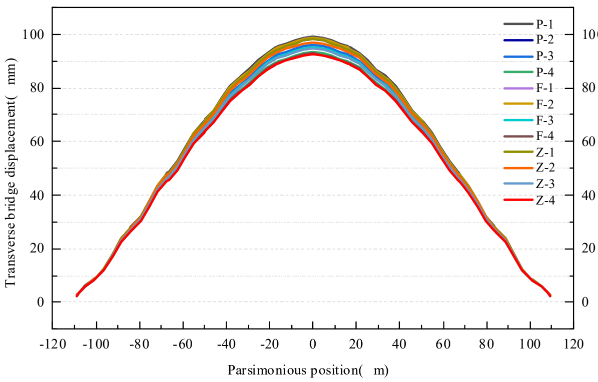

Figure 8. Maximum transverse bridge displacement of arch rib chord tube

Under the action of combination 4, according to Fig. 8 and Fig. 9, it can be concluded that: in each group of specimens, with the increase of core concrete strength grade, the embedding of stainless steel bellows and the addition of the combination of hoop reinforcement and tension reinforcement, the absolute value of transverse bridging displacement of arch rib chord pipe gradually decreases, which indicates that the improvement of elasticity modulus, i.e., the increase of the stiffness of the arch rib chord pipe, the transverse bridging displacement of the arch bridge structure will be reduced accordingly, and the two comparisons of the decrease is 6.8%, 6.4% and 6.4%, respectively. The decrease is 6.8% and 6.4% respectively, which is consistent with the vertical displacement of the arch rib chord tube.

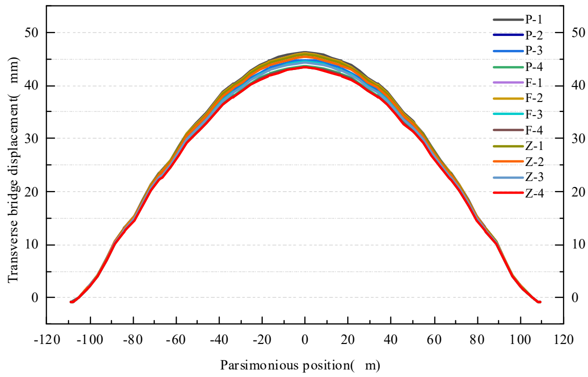

Figure 9. Minimum transverse bridge displacement of arch rib chord tube

5.4. Vertical Bridge Displacement Analysis of Bridge Deck Slabs

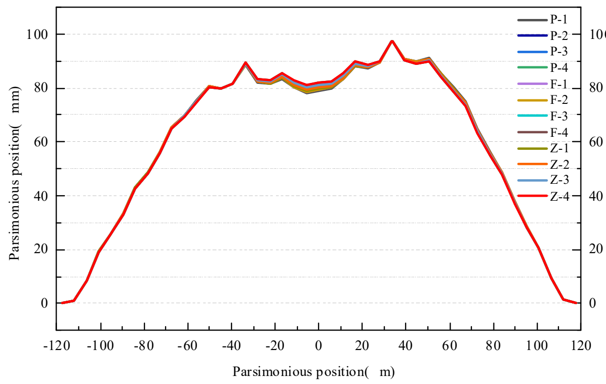

Figure 10. Maximum vertical displacement of bridge deck slab

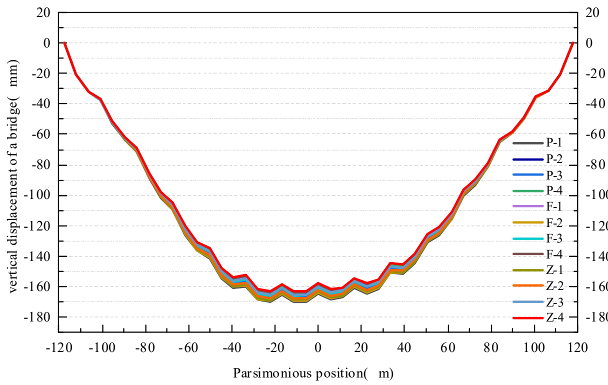

Figure 11. Minimum vertical displacement of bridge deck slab

Under the action of combination 4, according to Fig. 10 and Fig. 11, it can be concluded that: the vertical bridge displacement of the centerline of the bridge deck slab increases gradually with the increase of the core concrete strength grade, the embedding of stainless steel bellows, and the addition of the combination of hoop reinforcement and tension reinforcement, and the vertical bridge displacement gradually increases and the structure appears to be lifted up, and the law is the same as that of the vertical displacement of the arch rib and string tube, and the increase of the two comparisons is 3.8% and 3.9%, respectively, but the vertical displacement of the bridge is much smaller than the arch rib and string tube, and the increase in vertical displacement is much smaller than the arch rib and string tube. The two comparisons increased by 3.8% and 3.9% respectively, but the vertical displacement was much smaller than that of the arch rib chord tube.

6. Conclusion

1, With the increase of nominal modulus of elasticity of steel pipe concrete specimen, the vertical bridging displacement of arch rib chord tube increases gradually, and the structure appears lifting phenomenon, and the absolute value of paraxial displacement of arch rib chord tube decreases gradually;

2, the vertical bridge displacement law of the centerline of the bridge deck plate is similar to that of the arch rib chord tube, and the vertical bridge displacement gradually increases, and the structure appears to be lifting phenomenon, and the two comparisons increase by 3.8% and 3.9% respectively, but the increase of the vertical bridge displacement is much smaller than that of the arch rib chord tube;

3, in the arch bridge arch rib, deck plate and other components of deflection, deformation restrictions are more stringent in the project, especially the vertical bridge displacement, it is recommended to use the higher axial compressive stiffness of the steel pipe concrete arch rib.

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