Arch Bridges
ARCH´04
P. Roca and E. Oñate (Eds)

THE INFLUENCE OF RIGIDITY VALUE OF CONCRETE FILLED STEEL TUBULAR (SINGLE TUBE) ARCH RIB TO STATIC CALCULATION RESULTS

Jian-gang Wei[*], Lin-Qiang Zhao[†], Bao-chun Chen[*], Gui-han Peng[*]

[*]College of Civil Engineering and Architecture
Fuzhou University, Fuzhou 350002, China
E-mail: weijgfx@163.com

[†] Hangzhou Municipal Engineering Desing & Research Institue
No. 116, Wangsha Road, Hangzhou 310001, China

Key words: Concrete filled steel tube, Arch, Rigidity

Abstract. *The value of rigidity of cross-section component of CFST varies in different codes. Different rigidity will result in different internal forces, deflections as well as elastic stability of CFST arch. Based on the field test results of a CFST arch bridge, comparison of the influence of the CFST rigidity to the static calculation results using different codes is carried out in this paper. The conclusions from the analyses will be helpful and may act as a reference for the design of such kind bridge.*

1 INTRODUCTION

The compressive and flexural rigidities of CFST arch rib influence the predicted results of internal forces, deformation and stability of an indeterminate CFST arch bridge. The CFST arch rib comprises of steel and concrete, and its rigidities calculated by different codes or specifications have different values [i]. In this paper, an existing single tube CFST arch bridge, the Qunyi Bridge, is taken as the case study. Analyses results by FEM are compared with the field-testing results. The influence of the rigidities of CFST arch rib to the behaviors of the arch bridge is investigated with reference to six different design codes or specifications for CFST [ii ~vii.]

2 FIELD TESTING

The Qunyi Bridge, located in Fuan City, Fujian Province, China, is a half-through CFST arch bridge with a clear span of 46.00m and a clear rise of 15.333m, giving a rise-to-span ratio of 1/3. The bridge has two parallel arch ribs, each of which is a single steel tube of Φ 800mm×14mm, filled with C30 concrete. The bridge was constructed from 1996 to 1998 and opened to traffic in July 1998.

Field testing on the Qunyi Bridge was carried out in August, 1999. The arch rib on the upstream side was tested under three different load cases. Deflections on three cross-sections of the arch rib as well as the deck were measured by DSZ2 precision automatic level, at L/4, 3L/4 and the crown (Sections 2, 3 and 4), as shown in Fig.1. Four strain rosettes were mounted on each of the three cross-sections of the arch rib (spring, L/4 and the crown, i.e., Sections 1, 2 and 3 in Fig.1) to record longitudinal strains. The load effects on the CFST arch rib induced by the test loads are nearly equivalent to those induced by the design loads specified in The General Design Code of Highway Bridge and Culvert of China [viii].

The axle loads and weights of the eight vehicles are shown in Table 1. The field-testing was carried out at three locations with Load Case 1, 2 and 3. Load Cases 1 and 2 were expected to produce a maximum bending moment at the crown cross-section, and at the spring section, respectively. Load Case 3 was expected to produce a maximum horizontal thrust at the abutments. The locations of the vehicles in the longitudinal and transverse directions are shown in Fig 2. In Load case 1, there were three transverse rows of vehicles, whereas in Load Cases 2 and 3, there were two transverse rows, as given in Table 2. The test results are summarized in Tables 3 and 4, respectively.

3 LINEAR FINITE ELEMENT ANALYSES

A three-dimensional linear finite element model has been developed to analyze the Qunyi Bridge by using ANSYS, a finite element analysis software [ix]. The arch ribs are assumed to be fixed at the abutments. As a result, the model has a total of 376 frame elements and 158 shell elements with 380 nodes. Six design codes or specifications for CFST [ii]~ [vii] are compared herein.

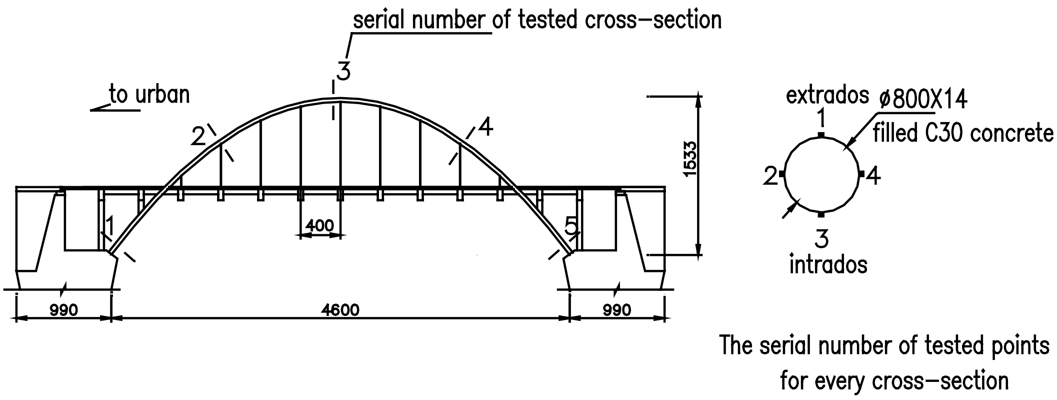
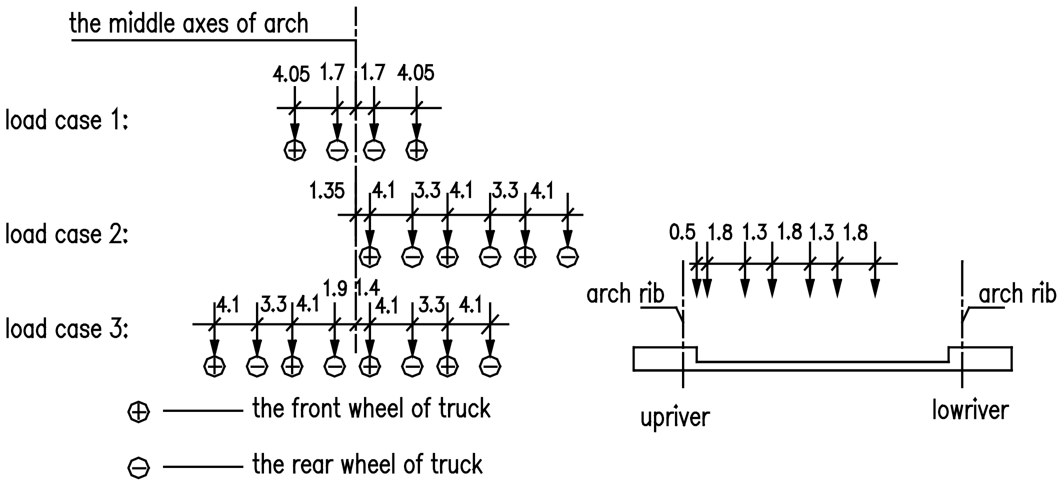


Fig. 1 Test arrangement of Qunyi Bridge (unit: cm)



(a) Longitudinal direction (b) Transverse direction

Fig. 2 Test load arrangement of Qunyi Bridge (unit: m)

Number	Front axle	Rear axle	Total
1	33.2	124.6	160.8
2	39.6	126.9	160.2
3	32.5	125.9	160.5
4	36.5	131.4	168.6
5	29.4	137.7	166.9
6	33.4	139.1	172.7
7	30.0	141.7	172.7
8	36.0	132.2	169.0

Table 1 Testing vehicle weight (unit: kN)

	Load Case 1	Load Case 2	Load Case 3
↓ To Urban	6 5 4	6 5	8 1
	3 2 7	4 2	6 5
		3 7	4 2
			3 7

Note: The figure in the table is the testing vehicle number

Table 2 Plans of the testing vehicles

Section	Load Case 1		Load Case 2		Load Case 3	
	Extrados	Intrados	Extrados	Intrados	Extrados	Intrados
1	-94	24	-114	43	-60	-1
2	11	-77	24	-84	-10	-26
3	93	64	-33	-12	-38	24
4	37	-55	-62	69	-46	-51
5	-20	20	55	-135	-86	-20

Table 3 Test results of longitudinal strain (unit: $\mu\varepsilon$)

Section	Load Case 1		Load Case 2		Load Case 3	
	Rib	Deck	Rib	Deck	Rib	Deck
2	-0.48	0.94	-4.47	-3.10	0.20	2.33
3	4.15	9.66	0.92	2.53	3.23	7.09
4	-0.33	1.04	9.10	9.37	1.98	3.24

Note: Positive figures in the table indicate the downward deflection.

Table 4 Test results of deflection (unit: mm)

Different calculation equations for compressive and flexural rigidities are listed in the second row of Tables.5 and 6, respectively, in which *Es* and *Ec* are elastic modulus of steel and concrete, respectively; *Is* and *Ic* are moment of inertia of steel tube and filled concrete, respectively; and *As* and *Ac* are area of steel tube and filled concrete, respectively. In this calculation, the elastic modulus of steel *Es* is taken as 206GPa and the elastic concrete modulus *Ec* is 30GPa.

The numerical values of the rigidities obtained from those different codes as well as some predicted responses of the structure are compared in Tables 5 and 6. When the effect of compressive rigidity is compared, the flexural rigidity, calculated by $EI=EsIs+EcIc$, is kept constant. Similarly, when the effect of flexural rigidity is compared, the compressive rigidity, calculated by $EA=EsAs+EcAc$, is kept constant.

In Tables 5 and 6, Δ denotes the predicted deflection, whose subscript indicates the section number as shown in Fig1, ε denotes the predicted strain with its second subscript “*e*” or “*i*” indicating extrados or intrados of the arch rib, respectively. The primed quantities Δ' and ε' are the tested deflection and strain, respectively. Stability factor is the elastic buckling load divided by the test load.

4 DISCUSSIONS ON RIGIDITY OF CFST ARCH RIB

4.1 Influence of rigidity on internal force and stress

Since the Qunyi Bridge is a statically indeterminate structure, different compressive and flexural rigidities of the arch rib will cause different analysis results. Therefore, the rigidity of the composite CFST arch rib is a strong research subject.

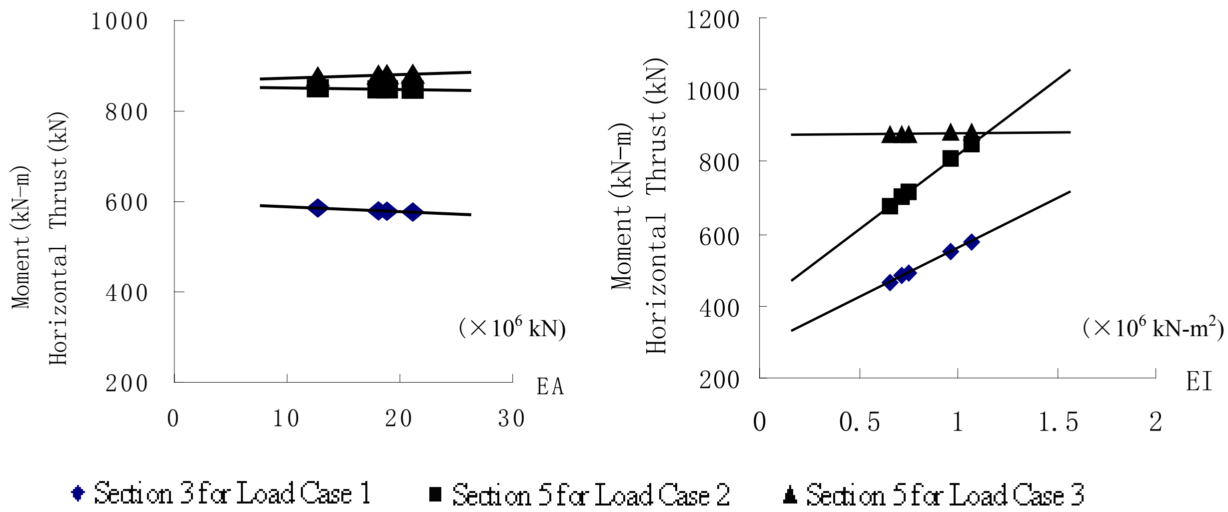
The rigidity of an arch rib will influence its predicted internal forces, especially bending moment, as well as stress. The bending moment at Section 3 (crown) for Load Case 1, the bending moment at Section 5 (spring) for Load Case 2 and the horizontal thrust at Section 5 (spring) for Load Case 3 as well as the stresses on the same sections are typically focused in this study. The relationship between internal forces, stresses and rigidities are shown in Figs.3 and 4.

Item		CESC[ii] AIJ[vii] BS5400 [vi]	JCJ[iii]	DL/T [iv]	AISC [v]
Rigidity	Equation	$E_sA_s+E_cA_c$	E_{sc}=0.85(ρE_s+ (1- ρ) E_c)		E_sA_s+0.4E_cA_c
	Value（10^{6}kN）	21.16	18.09	18.85	12.74
Load Case 1	Δ_3 / Δ'_3	1.40	1.46	1.44	1.58
	$\varepsilon_{3e} / \varepsilon'_{3e}$	2.67	2.67	2.67	2.72
	$\varepsilon_{3i} / \varepsilon'_{3i}$	2.73	2.74	2.74	2.78
	Stability factor	12.92	12.93	12.93	12.97
Load Case 2	Δ_4 / Δ'_4	1.58	1.61	1.58	1.63
	$\varepsilon_{5e} / \varepsilon'_{5e}$	2.75	2.76	2.75	2.77
	$\varepsilon_{5i} / \varepsilon'_{5i}$	2.00	2.01	2.00	2.01
	Stability factor	14.21	14.14	14.12	14.15
Load Case 3	Δ_3 / Δ'_3	1.20	1.28	1.30	1.64
	$\varepsilon_{5e} / \varepsilon'_{5e}$	1.08	1.12	1.13	1.10
	$\varepsilon_{5i} / \varepsilon'_{5i}$	2.05	1.83	1.83	1.94
	Stability factor	12.97	12.86	12.86	12.90

Table.5 Predicted results for different compressive rigidities

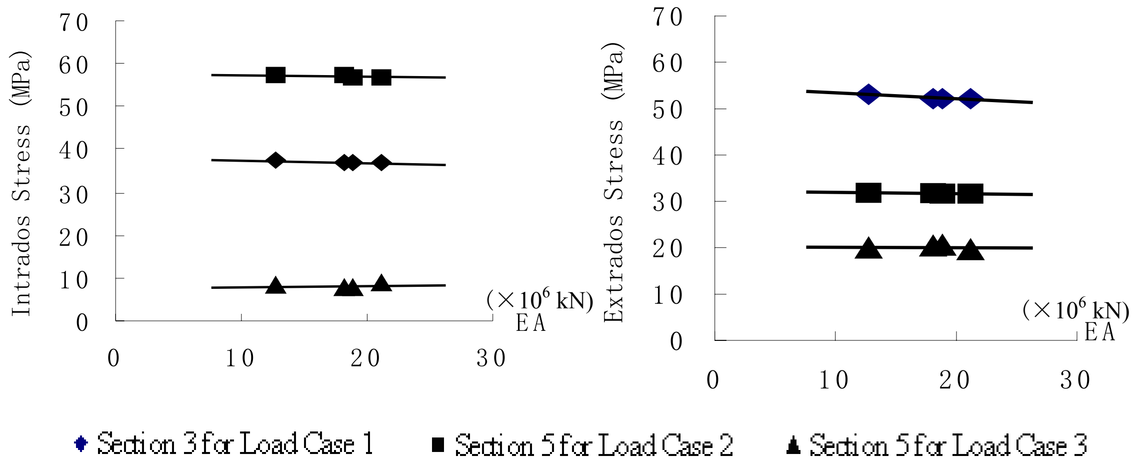
Item		CESC[ii] BS5400 [vi]	JCJ[iii]	DL/T [iv]	AIJ [vii]	AISC [v]
Rigidity	Equation	$E_sI_s+E_cI_c$	E_{sc}=0.85(ρ E_s+ (1- ρ) E_c)		E_sA_s+0.2E_c I_c	E_sA_s+0.8E_c I_c
	Value (10^6kN • m^2)	1.07	0.72	0.75	0.66	0.97
Load Case 1	Δ_3/Δ_3'	1.40	1.64	1.62	1.70	1.46
	$\varepsilon_{3e}/\varepsilon_{3e}'$	2.67	2.25	2.30	2.13	2.63
	$\varepsilon_{3i}/\varepsilon_{3i}'$	2.73	2.28	2.32	2.21	2.50
	Stability factor	12.92	9.24	9.56	8.56	11.85
Load Case 2	Δ_4/Δ_4'	1.58	1.82	1.79	1.90	1.63
	$\varepsilon_{5e}/\varepsilon_{5e}'$	2.75	2.26	2.30	2.19	2.49
	$\varepsilon_{5i}/\varepsilon_{5i}'$	2.00	1.68	1.72	1.59	1.98
	Stability factor	14.21	10.07	10.42	9.31	12.94
Load Case 3	Δ_3/Δ_3'	1.20	1.30	1.26	1.32	1.22
	$\varepsilon_{5e}/\varepsilon_{5e}'$	1.08	1.00	1.03	0.93	1.05
	$\varepsilon_{5i}/\varepsilon_{5i}'$	2.05	1.44	1.55	1.18	1.75
	Stability factor	12.97	9.14	9.46	8.45	11.75

Table.6 Predicted results for different flexural rigidities

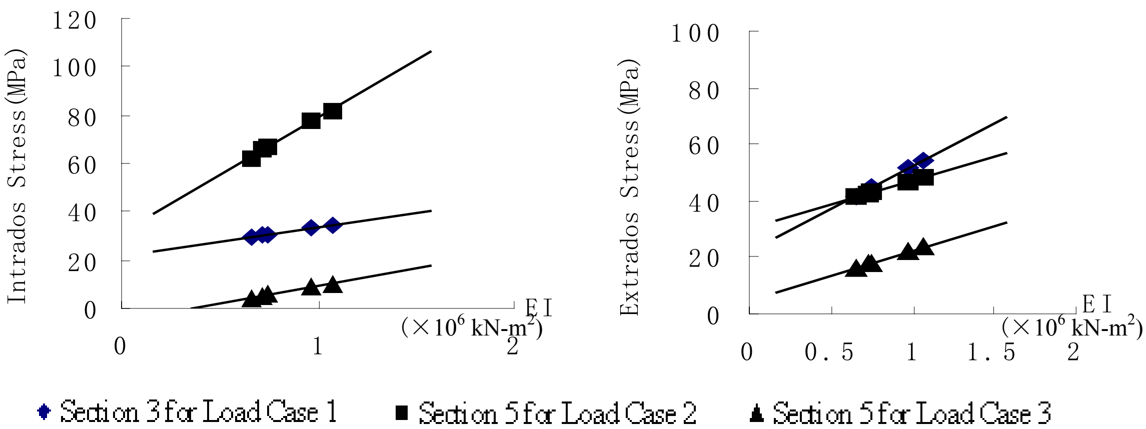


(a) Different compressive rigidity (b)Different flexural rigidity

Fig.3 Internal forces for different rigidities



(a) Different compressive rigidities



(b) Different flexural rigidity

Fig.4 Stresses for different rigidities

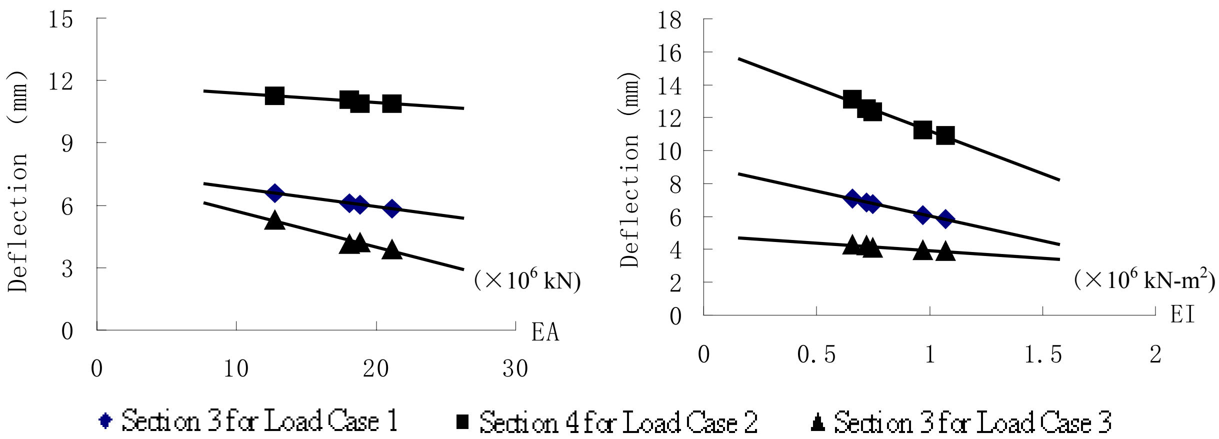
If the compressive rigidity of the arch rib increases by 66% (from 12.74×10^6kN to 21.16×10^6kN, as shown in Table 5), keeping the flexural rigidity constant, the internal force decreases only by 1.5% and the stress decreases by 2.0-12.0%. The influence of compressive rigidity on the internal forces and stresses is insignificant.

On the other hand, the influences of flexural rigidity are significant on bending moments and stresses but insignificant on the horizontal thrust. When the flexural rigidity increases by 62% (from 0.66×10^6kN • m^2 to 1.07×10^6kN • m^2, as shown in Table 6), the bending moments of Section 3 in Load Case 1 and of Section 5 in Load Case 2 increase by 24.3% and by 25.7%, respectively, whereas only 0.4% increment of the horizontal spring thrust is observed in Load Case 3. In the case of stress, whether it is in extrados or in intrados, it increases at least by 23.8% when the flexural rigidity increases by 62%.

Because the bending moments and stresses increase with the flexural rigidity of CFST arch rib, it is suggested to use the largest flexural rigidity calculated by CECS or BS5400 (*EI=EsIs+EcIc*) to calculate internal forces of the arch under design loads in order to guarantee the safety of the structure. And as the influence of compressive rigidity on the internal forces and stresses is insignificant, the compressive rigidity can be calculated with the same principle as for the flexural rigidity to simplify the calculation, i.e., *EA=EsAs+EcAc*.

4.2 Influence of rigidity on displacement

The compressive and flexural rigidities of arch do not equally influence the displacement in the CFST arch bridge, as demonstrated in Figs.5. In the given example, in Load Cases 1 and 2, for the 62% increase of flexural rigidity, the maximum displacement of the arch decreases by 20.1% and 19.5%, respectively; however, for the 66% increase of compressive rigidity, the maximum displacement decreases only by 3.3% and 12.6%, respectively. In contrast, when the compressive rigidity increases by 66% in Load Case 3, the maximum displacement decreases as much as 37.3%, whereas for the increase of the flexural rigidity by 62%, the maximum displacement decreases only by 8.1%. Therefore, when the compressive force is dominant in the arch, as in Load Case 3, the compressive rigidity will influence the displacement to a great extent and when the bending moment is a major action in the arch, as in Load Cases 1 and 2, the flexural rigidity will significantly affect the displacement.



(a) Different compressive rigidity (b)Different flexural rigidity

Fig.5 Deflection for different rigidities

Larger compressive and flexural rigidities result smaller displacements of the arch. Although, in this situation, the displacement calculated with larger rigidities are better match with the tested results; however, in an actual structure, the rigidities of the CFST arch rib will reduce under long term loadings. Therefore, the rigidities of a CFST arch smaller than those suggested in Section 4.1 should be taken into account to calculate the deflection in order to ensure fully deflection prediction for the safety and serviceability. The detailed calculation method needs further study.

4.3 Influence of rigidity on elastic buckling

In general, the critical axial thrust of an arch can be analogized to a straight column with an effective length given in Equation (1)

$$N_{cr} = \alpha \frac{EI}{S^2} = \pi^2 \frac{EI}{(kS)^2} \qquad (1)$$

in which, N_{cr}—elastic buckling thrust at a quarter point of the span;

E—Young's modulus;

I—moment of inertia of the cross section;

S—one half the length of the arch axis;

k—the effective length factor that depends on the type of arch and on the rise to span ratio.

From Fig.6, the stability factor (the elastic buckling load divided by the test load) obviously increases with the increasing flexural rigidity, regardless of the load pattern. But there is no direct relationship between the elastic buckling thrust and the compressive rigidity. The compressive rigidity will influence the elastic buckling thrust by affecting the internal force of the arch, but its influence is little as shown in Table 5. Therefore, the flexural rigidity is one of the important parameters for the critical elastic thrust of an arch while the influence of the compressive rigidity can be neglected. It is known that the elastic buckling loads are much higher than the tested ultimate loads of the model arches. Therefore it is reasonable to calculate the elastic buckling loads of a CFST arch with smaller flexural rigidity for safety consideration. So the detailed calculation method needs further study.

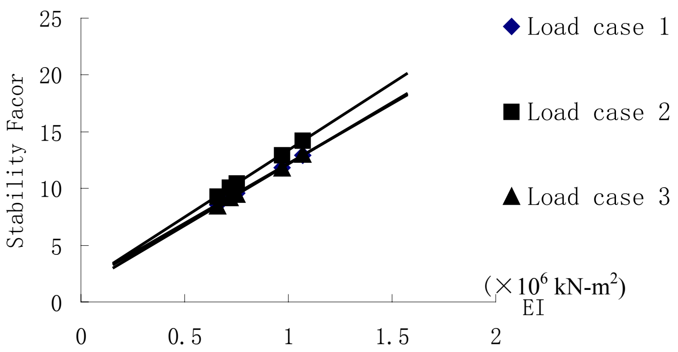


Fig. 6 Stability factor for different flexural rigidities

5 CONCLUSIONS

- The influence of compressive rigidity of CFST arch rib on the calculated internal forces is insignificant and can be ignored. But the calculated internal forces increase significantly with the increment of flexural rigidity. Hence, it is suggested to use the algebraic sum of rigidity of steel tube and core concrete as the rigidities of CFST arch rib ($EI= E_sI_s+E_cI_c$ *and* $EA= E_sA_s+E_cA_c$) to calculate the internal forces under design loads in order to guarantee the safety of the structure and to simplify the calculation.

- On the other hand, larger compressive and flexural rigidities result in smaller displacements of the arch. When the compressive force in an arch is the dominant force, the change of compressive rigidity influences the displacement much more than change of flexural rigidity or vice versa. The elastic buckling load of CFST arch is influenced little by its compressive rigidity, but is influenced by its flexural rigidity to a great extent. For the structural safety, small flexural rigidity of CFST arch rib should be considered during calculation of the deflection and the elastic buckling load of a CFST arch. The detailed calculation method needs further study.

REFERENCES

[i] Bao-chun Chen, *Examples (1) of CFST Arch Bridge (Chinese)*, China Communications Press, Beijing, China, 2002
[ii] Standard of the Construction Standard Committee of China，*Specification for Design and Construction of Concrete Filled Steel Tubular Structures (CECS 28：90)*, The Statistics Publishing House, Beijing, China, 1992
[iii] Standard of the Architectural Material Bureau of China, *Specification for Design and Construction of Concrete Filled Steel Tubular Structures (JCJ 01-89)*, Tongji University Press，Shanghai, China, 1989
[iv] Standard of the Economic and Trade Committee of China，*Specification for Design of Steel-Concrete Composite Structures (DL/T 5085 －1999)*, Electric Power Publishing House, Beijing, China, 1999
[v] AISC, *Load and Resistance Factor Design Specification for Structural Steel Buildings*, Chapter one, 1986
[vi] British Standards Institute, BS5400, Part 5, *Concrete and Composite Bridges*, 1979
[vii] Architectural Institute of Japan (AIJ), *Recommendations for Design and Construction of Concrete Filled Tubular Structures*, Japan, 1997
[viii] Standard of the Ministry of Communications of P. R. China，*Specification for Design of Reinforced Concrete and Prestressed Concrete Highway Bridge (JTJ 023-85)*, The People's Communication Publishing House, Beijing, China, 1985
[ix] ANSYS, *User's manual, revision 5.6,* Swanson Analysis System, USA, 1999.