STUDY ON STRESS CONCENTRATION FACTOR OF CFST K-JOINT

Hanhui HUANG, Kangming CHEN, Qingxiong WU

Fuzhou University, Institute of Civil Engineering, Fuzhou, CHINA.

e-mails: 18606936436@163.com, chen-kang-ming@163.com, wuqingx@fzu.edu.cn

SUMMARY

Focus on the K-joint of concrete filled steel tube (CFST) truss arch bridge, the influence of geometric parameters of CFST K-joint on the stress concentration factor (*SCF*) and the location of the hot spot stress are studied by finite element (FE) analysis employing the software of MSC. MARC, involving ratio of chord diameter to thickness (γ), ratio of brace diameter to chord diameter (β), ratio of brace thickness to chord thickness (τ), and angle between chord and brace (θ). It is found that the geometric parameters including γ, τ, β and θ only affect the value of the hot spot stress, and reducing the value of the geometric parameters above can improve the fatigue behaviour of the CFST K-joint.

Keywords: *CFST truss arch bridge, K-joint, stress concentration factor, ratio of chord diameter to thickness, ratio of brace diameter to chord diameter, ratio of brace thickness to chord thickness, angle between chord and brace.*

1. INTRODUCTION

In the view of the reason that the axial stiffness of the brace on the CFST K-joint is much larger than radial stiffness of the chord, the brace-to-chord intersecting line of the CFST K-joint becomes the vulnerable spot [1]. Because CFST arch truss bridge itself is a type of CFST structure, and the connected type is steel tube intersection directly, when the CFST K-joint bears axial force, concrete filled in the chord will exert swelling force on the wall of the steel tube. At the same time, both stress concentration and welding residual stress appear near the intersecting line of the CFST K-joint, which goes against the fatigue behaviour [2]. The fatigue distress above occurred on some actual CFST truss arch bridge. For example, Yajisha Bridge was open to traffic in 2000, but the fatigue cracks were found near the brace-to-chord intersecting line brace-to-chord in 2009, as is shown in Fig. 1. Besides, Shitanxi Bridge was open to traffic in 1998, but the fatigue cracks were found near the brace-to-chord intersecting line in 2013, as shown in Fig. 2.

After the history of more than 25 years, the number of existing CFST arch bridge exceeds 400, and CFST truss arch bridge accounts for about 13.6 percent [3]. With the development of the CFST truss arch bridge, the CFST K-joint of the existing and future CFST truss arch bridge will be bound to emerge the fatigue distress like Yajisha Bridge and Shitanxi Bridge. Currently, facing the design of the CFST K-joint, designers usually simplify them as traditional skeletal structure to calculate the internal force and nominal stress, and ignore the local stress of the CFST K-joint. What's more, some designers don't take the contribution of the concrete filled in the chord into account, and regard the CFST K-joint as HSS K-joint, which is excessively conservative and uneconomic. At the same time, reference [4] pointed out that the maximum *SCF* of both the chord and the brace on HSS K-joint was found on the saddle point, but CFST K-joint appeared on the crown point under the axial force.

Fig. 1. *Fatigue distress of Yajisha Bridge.*

Fig. 2. *Fatigue distress of Shitanxi Bridge.*

China actively has carried out relevant research on the joints in the past few years, but it mainly focuses on the HSS joint of the offshore structure. Compared to the HSS joint, study on the CFST K-joint is relatively backward, especially on the K-joint of CFST truss arch bridges. In addition, study on the K-joint of CFST truss arch bridges mainly centres on the loading test. At present, based on Chongqing Zhongxian Yangtze River Highway Bridge, Beipanjiang Rail Bridge, Caoejiang Bridge and Wushan Yangtze River Highway Bridge, Fan Wenli and Qian Yongjiu conducted some reduced-scale model fatigue tests, and obtained a certain achievement, but it didn't be promoted in a wide range due to the limited number of the tested model. Besides, relevant codes published in China don't give the specific design criteria of the CFST K-joint. *Specifications for Design of Highway Concrete-filled Steel Tubular Arch bridge*(JTG/T D65-06—2015) [5], *Technical code for concrete-filled steel tube arch bridges*(GB 50923-2013) [6], *Technical Specification for Concrete Filled Steel tubular arch bridges*(DBJ/T 13-136-2011) [7] and *Code for Design of Highway Concrete-filled Steel Tube Arch bridges*(CQJTG/T D66-2011) [8] are widely used on the fatigue design of CFST K-joint, but those codes only provide the structural type of the CFST K-joint and the fatigue allowable stress range, but don't give specific check formula. Moreover, those codes also don't declare that whether the geometric parameters affect the fatigue behaviour of the CFST K-joint and what the regularity is.

In summary, it is greatly significant to do some research on the fatigue behaviour of CFST K-joint, especially the influence of the geometric parameters on it. Because *SCF* of the CFST K-joint is typical index, this paper focuses on the *SCF* of the K-joint of CFST truss arch bridge based on the finite element analysis, and obtains the distribution of *SCF*. In addition, the regularity that the geometric parameters have influence on the fatigue behaviour of CFST K-joint and some suggestions that can improve the fatigue life of CFST K-joint are also given in this paper.

2. FINITE ELEMENT ANALYSIS

2.1. Method of finite element models

In order to analyse the distribution of hot spot stress along the brace-to-chord intersecting line of the CFST K-joint, finite element method and test method are usually adopted. Although the test method has the advantage of high accuracy, it needs a great deal of cost and time. Besides, it lacks flexibility which makes it become low efficiency. Compared to the test method, the finite element method can overcome the disadvantages above, so this paper adopts the finite element method validated by the existing tested result before to analyse the distribution of hot spot stress along the brace-to-chord intersecting line of the CFST K-joint. It can not only make sure the result is accuracy, but also reduce the computation period.

2.2. Finite element models of CFST K-joint

Considering that the CFST K-joint consists of both steel tube and concrete, and both of them act upon the K-joint together, so choosing suitable element type becomes a key aspect. According to the function of the finite element software of MSC.Marc, its shell element can acquire the result along the direction of the thickness. Besides, the thickness of steel tube is thin enough and reference [9] also used the shell element to simulate the K-joint of the steel tube. To sum up, this paper selects the shell element to simulate the steel tube of the CFST K-joint. As to the concrete, usually solid element is used to simulate it.

In the view of the fact that the distribution and the maximum value of the hot spot stress appear near the brace-to-chord intersecting line of the CFST K-joint, finite element mesh must be subdivided in the area of hot spot stress compared to other areas. In other words, the finite element mesh includes two parts. One is fine region, the other is rough region. By means of the approach above, the intense change of the hot spot stress inside the hot spot stress area can be clearly reflected. At the same time, it also reduce the calculating time and improve efficiency. Fig. 3 has shown the geometric shape of the typical K-joint. Fig. 4 has shown the finite element mesh of the CFST K-joint.

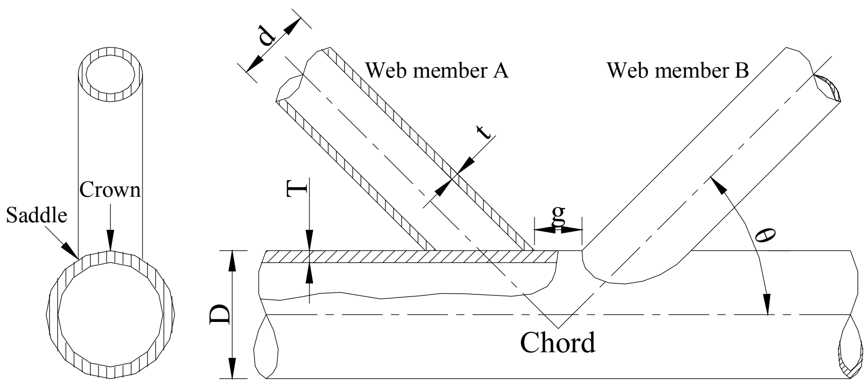

Fig. 3. *Configuration of CFST K-joint.*

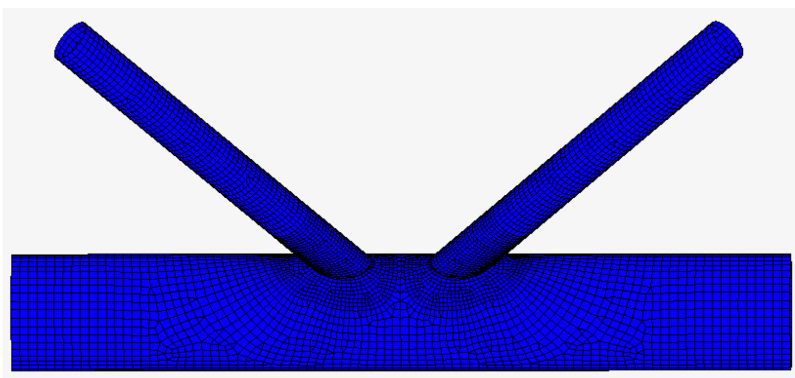

Fig. 4. *Mesh of CFST K-joint.*

2.3. Validity of the finite element analysis

To validate the reliability of the finite element model of the CFST K-joint, adopting the same method and geometric parameters as the reference [10], this paper uses the MSC.MARC to establish a finite element model of the CFST K-joint. The results obtained using two methods respectively are presented in Fig. 5. Figure 5 illustrates that under the condition of the axial force, although the value of the hot spot stress near the brace-to-chord intersecting line of the CFST K-joint have some difference between the theoretical value acquired by finite element analysis and those of the reference [10], both of them show that maximum *SCF* of chord and brace appear on the crown, and the changeable tendency of both the theoretical value and test value in reference [10] is very similar. Therefore, the result obtained from the finite element analysis can reflect the stress state of the CFST K-joint under the axial force, which namely proves that the finite element analysis is reliable.

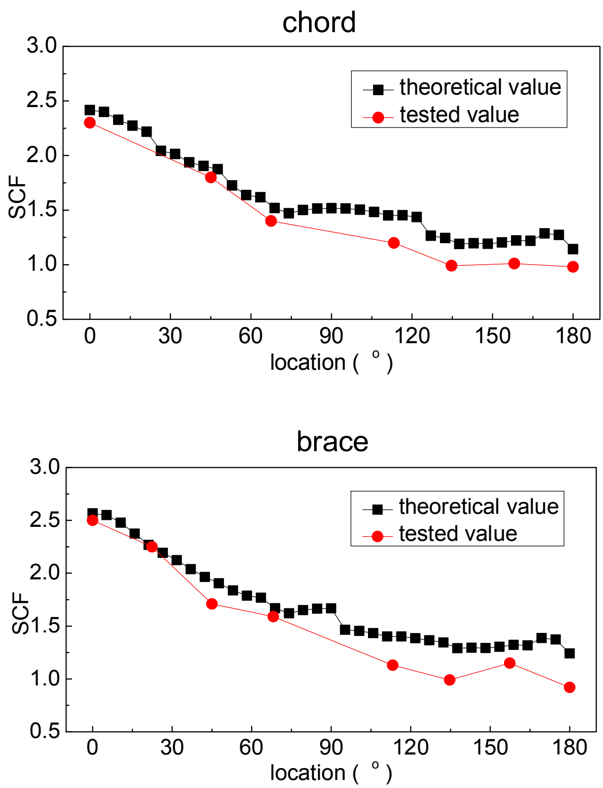

Fig. 5. *Comparison of results obtained using two methods respectively.*

2.4. Boundary condition

Based on an actual half-through CFST truss arch bridge in China, this paper firstly uses the software of MIDAS CIVIL to analyse the full bridge, which consists of 1302 nodes and 3462 elements in the model and is shown in Fig. 6. It is found that the K-joint of the CFST truss arch bridge mainly bears axial force not only chord but also brace, on the other hand the bending moment and the shear force have little influence on the CFST K-joint. Then choose the CFST K-joint of the CFST truss arch bridge which is under the most unfavourable state, and exact the axial force that chord brace bear as the loading value of finite element model. In summary, the boundary condition of the finite element model is that one side of the chord is fixed constraint, the other side bear the axial force. As to the brace, one bears axial compressive force, the other bear axial tensile force, which is illustrated by Fig. 7.

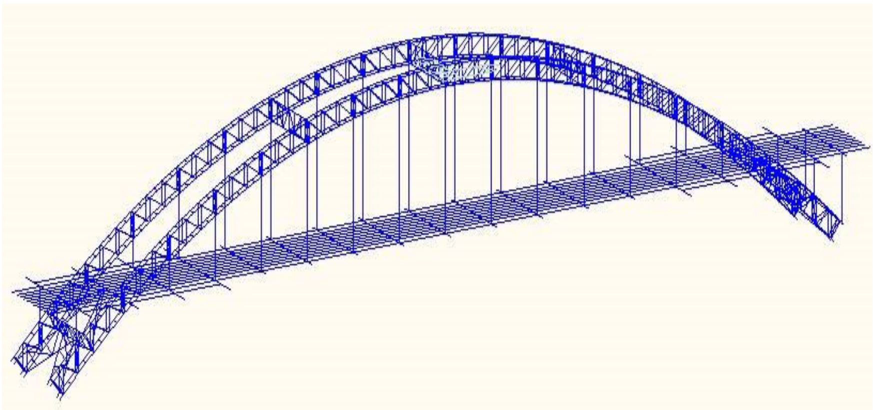

Fig. 6. *Finite element model of full-bridge.*

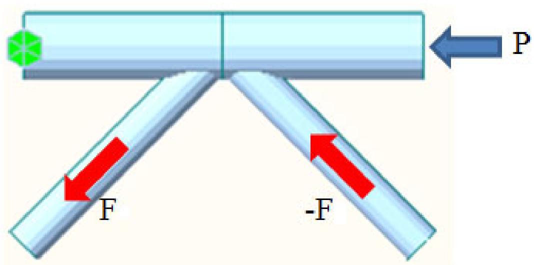

Fig. 7. *Boundary condition.*

3. INFLUENCE OF GEOMETRIC PARAMETERS ON THE CFST K-JOINT

3.1. Geometric parameters of the CFST K-joint

Take the results of foreign codes, Chinese codes and relevant researches on the K-joint into account, and it is found that not only the self-characteristics of the steel tube will affect the fatigue behaviour of K-joint, but the geometric parameters of the K-joint may have great influence on that of K-joint. The regulation in China that express the key geometric parameters above is according to those who are given in International conference on offshore steel held in Paris in 1981. On the whole, the key geometric parameters that may influence the fatigue behaviour of CFST K-joint includes ratio of chord diameter to thickness ($\gamma=D/2T$), ratio of brace diameter to chord diameter ($\beta=d/D$), ratio of brace thickness to chord thickness ($\tau=t/T$), and angle between chord and brace (θ). Where D is the diameter of the chord, T is the thickness of the chord, d is the diameter of the brace and t is the thickness of the brace. As shown in Fig. 3.

Compared to the research results by Bai Yuhui [10], *DNV* [11], *CIDECT*(8) [12], Diao Yan [13], Yang Sheng [15], and Tong Lewei [16], it illustrates that the geometric parameters above are limited in a suitable range. Detailed range of them is summarized in Tab. 1.

Table 1. *Statistics of geometric parameters on the K-joint.*

Geometric parameter / Code or researcher	θ	γ	τ	β	remark
Bai Yuhui	30^o-45^o	5-20	0.4-0.7	0.3-0.6	CFST
DNV	20^o-90^o	8-32	0.2-1.0	0.2-1.0	HSS
CIDECT(8)	30^o- 60^o	10-35	0.25-1.0	0.35-1.0	HSS
Diao Yan	45^o	22.85	0.8	0.55	CFST
Yang Sheng	45^o - 60^o	18.25	0.667	0.667	CFST
Tong Lewei	45^o	12-30	0.25-1.0	0.3-0.6	CFST

In the meanwhile, considering the fact that providing θ is too small, the welding difficulty will increase, and weld root don't tend to be fully penetrated, which is against the quality of the weld, *Code for design of Steel structures*(GB 50017-2003) [15] requires that θ should be more than 30^o. Besides, θ of actual project is usually less than 60^o.

To sum up, in order to study the influence of geometric parameters of θ, γ, τ and β on the CFST K-joint, the range of the geometric parameters is $30^o<\theta<60^o$, $8<\gamma<36$, $0.2<\tau<1.0$ and $0.2<\beta<1.0$. Controlling variables method has been used. Detailed steps contain that when finite element model analyses one geometric parameter influencing the fatigue behaviour of the CFST K-joint, the others must remain the same. At the same time, among the finite element models, one of them is viewed as a standard model, whose geometric parameters is the same as an actual bridge, and others compare with the standard model. Therefore, the number of the finite element models is 12. The detailed geometric parameters of the finite element models are shown in Tab. 2.

Table 2. *Geometric parameters used by finite element analysis*

Model	θ	γ	τ	β	Model	θ	γ	τ	β
Standard model	45^o	34	1	0.4	Model6	45^o	34	0.3	0.4
Model1	30^o	34	1	0.4	Model7	45^o	34	0.5	0.4
Model2	60^o	34	1	0.4	Model8	45^o	34	0.7	0.4
Model3	45^o	8	1	0.4	Model9	45^o	34	1	0.5
Model4	45^o	16	1	0.4	Model10	45^o	34	1	0.7
Model5	45^o	24	1	0.4	Model11	45^o	34	1	0.9

3.2. Influence of ratio of chord diameter to thickness γ

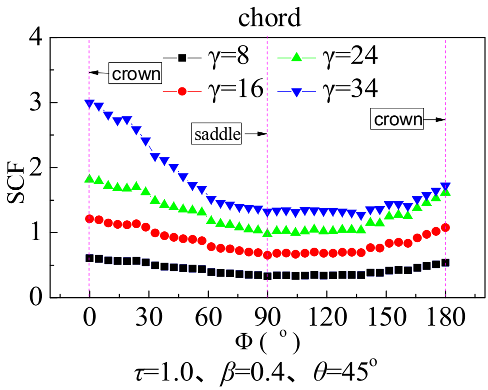

Fig. 8. *SCF distribution on chord.*

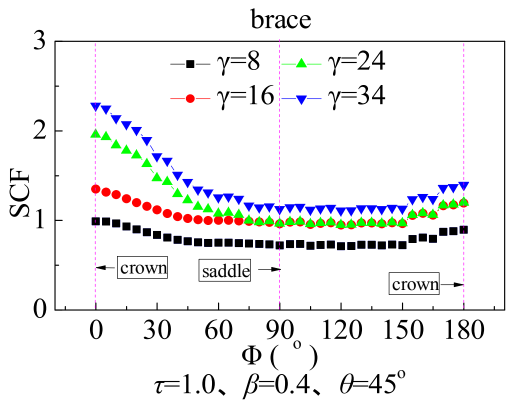

Fig. 9. *SCF distribution on brace.*

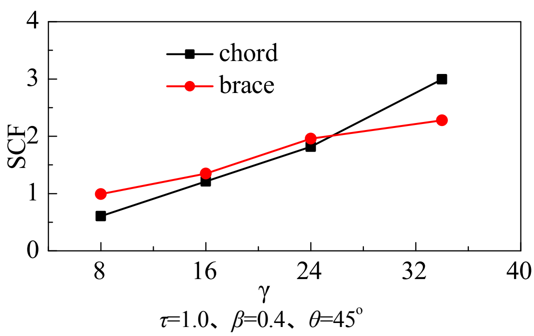

Fig. 10. *Effect of* γ *on the maximum SCF.*

Fig. 8 and Fig. 9 indicate that the geometric parameter γ only affects the value of the hot spot stress, but don't change the location of the hot spot stress. Besides, no matter how much γ is, the maximum *SCF* appears on the crown of the CFST K-joint, and the saddle of CFST K-joint remains the minimum *SCF*. Fig. 10 shows that the maximum *SCF* of both chord and brace increases linearly with the geometric parameter γ increasing. When the value of γ is from 8 to 24, the maximum *SCF* of brace is more than that of chord, but when the value of γ exceeds 24, the maximum *SCF* of chord is more than that of brace. In other words, reducing the value of γ can effectively improve the fatigue behaviour.'

3.3. Influence of ratio of chord thickness to brace thickness τ

Fig. 11 and Fig. 12 indicate that the influence on the CFST K-joint of the geometric parameter τ is similar to those of the geometric parameter γ. Fig. 13 shows that the maximum *SCF* of both chord and brace increases linearly with the geometric parameter τ increasing. When the value of τ is from 0.3 to 0.5, the maximum *SCF* of brace is more than that of chord, but when the value of τ exceeds 0.5, the maximum *SCF* of chord is more than that of brace.

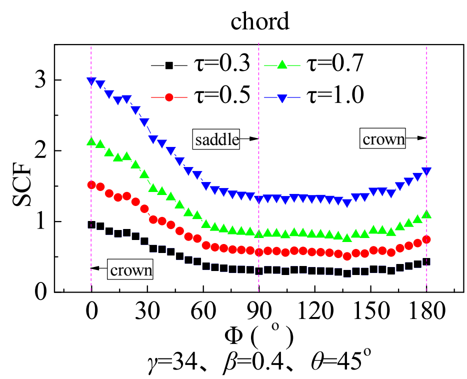

Fig. 11. *SCF distribution on chord.*

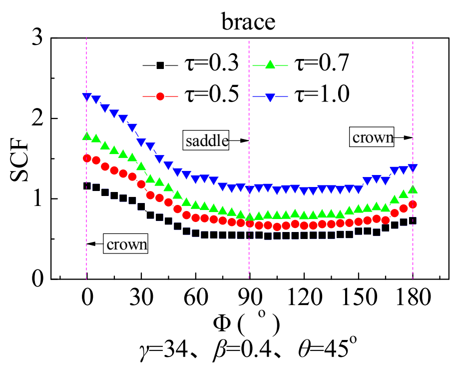

Fig. 12. *SCF distribution on brace.*

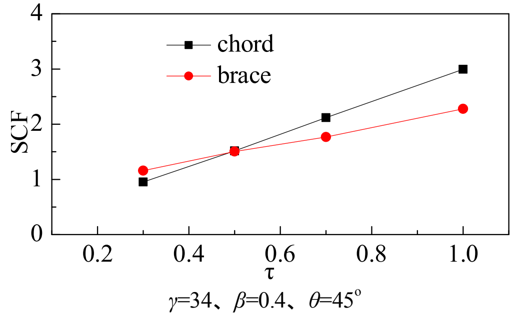

Fig. 13. Effect of τ on the maximum SCF.

3.4. Influence of ratio of chord diameter to brace diameter β

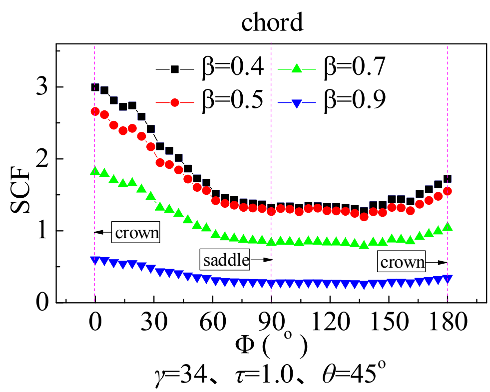

Fig. 14. SCF distribution on chord.

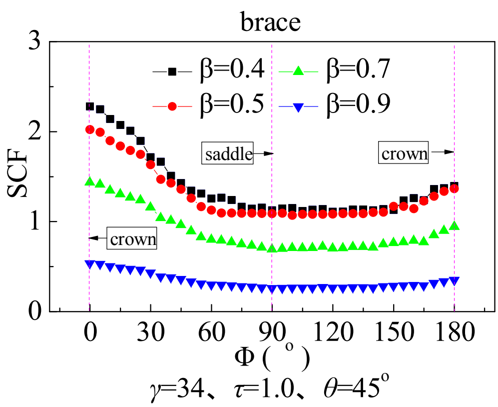

Fig. 15. SCF distribution on brace.

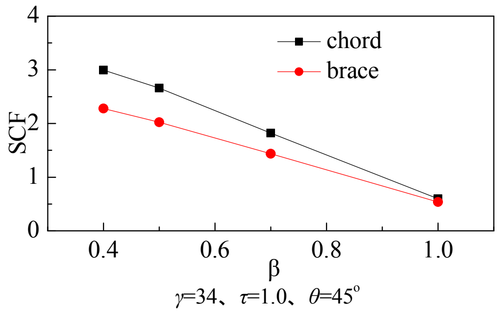

Fig. 16. *Effect of* β *on the maximum SCF.*

Fig. 14 and Fig. 15 indicate that the influence on the CFST K-joint of the geometric parameter β is similar to those of γ and τ. Fig. 16 shows that the maximum *SCF* of both chord and brace decreases linearly with the geometric parameter β increasing. The maximum *SCF* of chord is more than that of brace, but the maximum SCF of brace gradually tends to be equivalent. Therefore, increasing the value of the geometric parameter β can effectively improve the fatigue behaviour.

3.5. Influence of angle between chord and brace θ

Fig. 17 and Fig. 18 indicate that the influence on the CFST K-joint of the geometric parameter θ is similar to those of the geometric parameter γ, τ and β. Nevertheless the influence on the CFST K-joint of θ is more complex compared to the others. With the variation of the geometric parameter θ, the *SCF* of the other crown increases. Fig. 19 shows that the maximum *SCF* increases with the geometric parameter θ increasing. Besides the maximum *SCF* of the brace is always less than that of the chord with the variation of θ. Taking improving the fatigue behaviour and welding into consideration, θ needs to be limited to 45° as soon as possible.

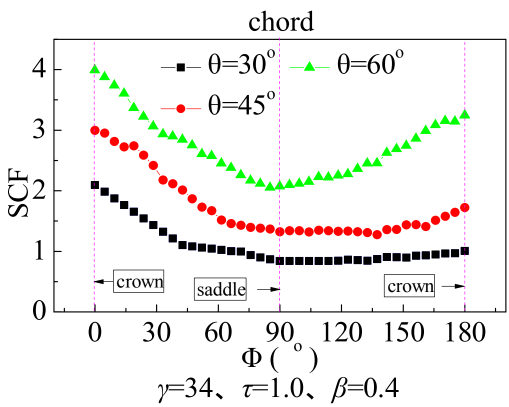

Fig. 17. *SCF distribution on chord.*

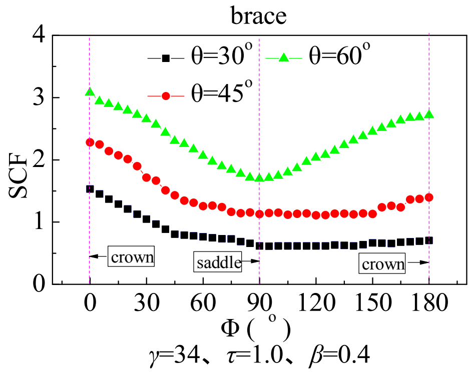

Fig. 18. *SCF distribution on brace.*

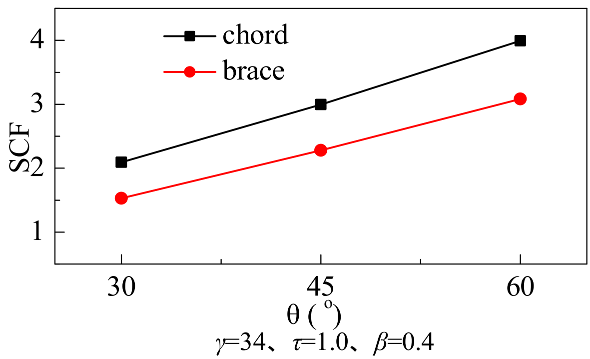

Fig. 19*. Effect of θ on the maximum SCF.*

4. CONCLUSIONS

In this study, the distribution of *SCF* and the regularity that the geometric parameters influence on the fatigue behavior of CFST K-joint have been found. Furthermore, some suggestions that can improve the fatigue life of CFST K-joint are also given in this paper. Main conclusions can be summarized as follows.

1. The geometric parameters including γ, τ, β and θ only affect the value of the hot spot stress. Moreover, with the variation of geometric parameters above, the maximum and minimum *SCF* appear on the crown and saddle point of the CFST K-joint, respectively.

2. The value of the maximum *SCF* of both chord and brace increases with the geometric parameter γ, τ and θ increasing, but decreases with the geometric parameter β increasing.

3. It is highly effective for improving the fatigue behaviour of the CFST K-joint by reducing the value of the geometric parameter γ, τ and θ, or increasing the geometric parameter β.

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