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The study on stress concentration factor and fatigue behavior of CHS-CHS X-joints with concrete-filled braces

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Abstract: The using of concrete-filled composite tubular joints in bridge has been occurred for many years, and is increasing in the future years. As a result, the reliability of these joints under fatigue must to be investigated to avoid any potentially catastrophic. This paper describes experimental and Finite element investigation on stress concentration factors (SCFs) of Circle-Circle X-joint with concrete-filled brace. This CHS-CHS X-joints with concrete-filled brace were strain gauged and tested under static loading at hot spot locations , where cracks are likely to propagate. The corresponding finite element analysis was used to simulate the non-uniform stress distribution along the brace and chord intersection region. The data comparison between the experimental and finite element analysis is proving the model of finite element reliably. Therefore, 320 Finite Element models with different non-dimensional geometric parameters β (ratio of brace width to chord width),2γ(ratio of chord width to chord thickness),τ(ratio of brace thickness to chord width) and concrete strength were created. Based on above results, by use of regression analysis, the paper derive a new set of parametric equations in terms of several non-dimensional geometric β、2γ、τ and concrete strength 。In addition to , this paper has proved that the significantly reduce when circular hollow section(CHS) X-joints were filled with concrete subjected to axial tension loading.

1 Introduction

There are many literatures shows that a lot of study has been carried out on empty (or called hollow)tubular joint in respect of fatigue load, such as Romeijn[1], Efthimiou and Durkin[2], van Wingerde[3]and Zhao et al.[4], and so on. These trussed constructions have widely used in bridges, offshore platforms, etc.When severe cyclic load has been putting pressure onto these tubular structure, fatigue damage may cause fatigue cracks. To the long span steel truss bridge, joint fatigue damage is the main - type destroys.At the weld toe of the brace where the fatigue cracks are always initiated due to notch effect at the brace-chord junction. The fatigue design rules of empty welded tubular nodal joints can be found in different fatigue design guidelines adopted in Europe, North America, Australia and the rest of the world(EC3[5], Zhao et al.[6], IIW[7], SAA[8], API[9]).

A very effective method that often be used to reduce stress concentrations in the brace, which cause by in-plane bending (IPB) and out-of-plane bending (OPB), is through concrete-filling of the brace. Truss bridge with concrete-filled chord has been used for many years, and is using for the future. For example, Han and Yang[10], Packer and Fear[11], Zhou and Chen[12].

In this paper, six concrete-filled circular hollow section X-joints were manufactured and tested. The result of test contains six serials of β、2γ、τ. All specimens were subjected to axial pressure loading. On the other hand, six model which has same size of with test specimans, created by abaqus to analyze the concrete-filled tubular joint. By rational meshing, the paper analyzed the stress of the joint accurately and compared with the experimental date. It can be conclude that the finite element model can be used in simulating that the concrete-filled circular hollow section X-joints subjected to axial load. Then the paper created 320 models with different non-dimensional geometric parametersβ、2γ、τ and concrete strength in order to conduct for the influence of these parameters on brace and chord SCFs(stress concentration factor) and fatigue behavior in X-joints subjecting to the axis load. Based on above results, by use of regression analysis, the paper derive a new set of parametric equations in terms of several non-dimensional geometricβ、2γ、τ and concrete strength.

2 Hot spot stress method

2.1 Hot spot location

Hot spot stress is the maximum structure stress mostly located in the weld toe of brace and chord. Fatigue crack are common at position like that. In order to simulate numerically this kind of complex practical problems, the contact of steel tube and concrete in the concrete-filled steel tubes still should be considered when building the analysis model. The contact problem involves the stress concentration, boundary nonlinear and material of geometric nonlinear problems. We were usually used both finite element method(FEM) and experimental stress analysis to estimate the SCFs of welded tubular joint. In recent years, according to both FEM and strain gauge measurement method, there were a lot of parametric formulas have been reported. Such as, Toprac et al.[16] concluded from the test data ,that came from one of the early experimental works on the fatigue behavior of circle tubular joints, at the weld toe where the crack initiation at occurred on the highest stress, and the stress concentration was an important factor. The SCF formula for T-joints and Y-joints that based on FEM derived by Gibstein[17].By means of finite element method(FEM) and experimental stress analysis, Macdonald and Haagensen[18]proposed parametric equation that can predict the SCFs of aluminum RHS T-joints.

2.2 Extrapolation method

Based on two extrapolation method(linear and quadratic extrapolation)proposed in the CIDECT Design Guide No. 8[19], which provide a guidance for determining the locations of strain gauge for tests, the boundaries of the extrapolation region for CHS joints were shown as Table 4, Fig. 1. By obtaining the reading of strain gauge in the weld toe, the SNCF could be obtained by using formula as follow:

$$SNCF_{\mathrm{CHS}} = \varepsilon_{\max} / (\varepsilon_{ax} + \sqrt{(\varepsilon_{\mathrm{IPB}}^2 + \varepsilon_{\mathrm{OPB}}^2)}) \quad (1)$$

The $\varepsilon_{\max}$ is the extrapolated maximum strain, $\varepsilon_{\mathrm{ax}}$, $\varepsilon_{\mathrm{IPB}}$ and $\varepsilon_{\mathrm{OPB}}$ are nominal strain components caused by axial compression, IPB loading and OPB loading, respectively.

And SNCF can derivated to SCF based on the formula as follow:

$$SCF_{\mathrm{CHS}} = 1.2 SNCF_{\mathrm{CHS}} \quad (2)$$

2.3 Purpose of this study

The most of previous studies on the SCFs of welded tubular joint were mainly on hollow steel tubular joints. This paper focuses the research on concrete-filled tubular joints. Because of the development of concrete-filled tubular joints is becoming more and more quickly, the SCFs of concrete-filled tubular joints need to be studied for fatigue behavior. Compared the fatigue behavior of hollow tubular X-joints with concrete-filled tubular X-joints were researched. In the CIDECT Design Guide No.8[19] ,the design guidelines can be found.

3 Experimental investigation

3.1 Experimental design

In this experiment, all X-joint specimen have used same experimental equipments. The stress concentration factor testing of the X-joints specimens were proceed in the Structures Laboratory, School of urban construction, Yangtze University. The joint specimen was shown in Fig. 2. Each X-joints consist of horizontal CHS chord and vertical CHS brace filled with concrete. The section properties of the joint specimen are listed in Table 1. Geometric parameters $\beta=d_B/d_C$, $\tau=t_B/t_C$, $2\gamma=d_C/t_C$ are shown in Fig. 2, using the dimensions of all specimens as detailed in Table 1. The joint specimens were fabricated on the basis of structural steel tubes API 5L [20]. Weld process of joints follow the CIDECT specification [19]. In the test rig, one end of chord and each end of brace were welded onto the 10mm thickness end plates and bolted directly onto the steel truss, as shown in Fig. 3.

3.2 X-joints Specimen labeling

According to the shape of these specimens, chord or brace tubular that concrete filled with, the specimens were numbered with prefix ‘XBC’. The first char ‘X’ denotes X-joint; The second ‘B’ denotes Brace; The third char ‘C’ denote concrete-filled.

According to GB/ T 228- 2002《 Metallic materials-Tensile testing at ambient temperature》, the metallic materials was conducted by the standard method of metal tension test, as shown in Table 2.

According to 《Standard for test method of mechanical properties of ordinary concrete》, concrete mechanical property conducted by mechanical property experiment. The results are as follows, the concrete cube compressive strength is 45.5MPa, and the elasticity modulus is 3.09×10^4MPa

3.3 Loading Plan

According to 《Code for design of steel structures》in china, X-joints were computed as hollow tubular joint before experiment, whose result could be used as pre determined loads that shown in Table.3. Based on estimated loading, the degree of loading was selected and the grade of loading was determined. The grade of loading as follow: when in preload stage, the 10 percent of predetermined loads was classed as one grade and total three grades were loaded; when in formal loading, every one grade is 10KN,pausing the applied loads for 1 or 2 minutes the strain readings were recorded(Because it must be considered the time lag and also stress relaxation caused by the data acquisition system), continue loading between each grades. Loading was stopped if plastic yielding was achieved, thus the every degree of loading must be adjusted.

3.4 Hot spot strain (HSSN) measurement

Due to the complexity of stress distribution, for test the stress degree and distributive rule, by using extrapolation approach, three-directional straingages were distributed along the weld areain order to obtain the hot spot strains. Because of the symmetrical intersections, there were 10 test points distributed on brace numbered T1 to T10 ， five on chord and five on brace. These strain gauges were distributed around the whole chord/brace intersection on both brace and chord at 0°、45°、90°、135°、180°,which followed the linear extrapolation area[19].All three-directional straingages were distributed in 15mm away from the weldingseam to reduce the influence of weldingseam on strain test. As shown in Figure 4.

3.5 Experimental result

SCFs values achieved from strain gages that placed perpendicular to the welding seam were shown in Fig.5. At the brace intersection, as shown in Fig. 5a , the SCF curves were parabolic curves. The maximum stress concentration factor occurred on near the saddle point of brace. As shown in Fig. 5b,at the chord intersection, the maximum stress concentration factor occurred on near the saddle point

3.6 Finite element model

Finite element model has been developed rapidly since 2070s. In this paper , general finite element analysis software ABAQUS was used by the numerical research SCF distribution of CHS-CHS X-joints with concrete-filled braces. The basic material properties and specimen dimensions that obtained from experiment was used in FEA(finite element analysis). Although there were many factors effected on the SCF distribution of the X-joints, only geometrical influences were considered in the finite element models. Compare with the 8-node linear brick(C3D8) ,the 8-node linear brick incompatible mode (C3D8I) is more improved, so the C3D8I-element was used in this paper's finite element models. As shown in Fig.6, based on the previous researches on finite element simulation, in the direction of thickness, the chordtubule of X-joint were divided into two elements. It can be seen in Fig.6. the welding seams area of X-joints were separated into nine elements. By comparing with different mesh generation for finite element computation, it was found that in the thickness direction of chord was the two-element mesh generation and in the welding area was nine-element, which could use reasonable computational time achieve accurate results. In the same way that shown in Fig.6. finite element analysis six specimens were created by Abaqus.

The elements of chord and brace were farer away from the intersection, the smaller influence of them on the maximum of SCF, so their mesh density could be ignored. In order to make computing speed more rapidly, the density of those elements that far away from the intersection should be fewer. In other word, the density of elements that near to seam area should be finer due to their more influence on stress concentration. Considered both efficiency and precision of FEA, based on repeated adjust the FEA of X-joints for experimental results,the elements far away from the weld area were arranged to 4mm, the elements near to weld area were arranged to 3mm and in the weld area were arranged to 2mm. The whole elements of each FEA model was about 80000. The amount of two weld areas was about 11000.

The condition of boundary and loading were the same as the experimental test.

3.7 Verification of finite element model

The FE models for the X-joints with concrete-filled braces must be verified by comparing the reading of three-directional strain gages in experimental test and the computational results of corresponding position in FE models before the FE models were used in parametric study. The test specimens were welded by full penetration groove welds, and the average weld size was 1.5 times the minimum between chord thickness and brace thickness. All parameters such as welding size, brace size, chord size, boundary condition of FE models must be in accordance with those of the experimental rest specimens. Every FE model were subjected to axial tension loading. As shown in Fig.4. in the FEA, the SCFs were computed in the same direction as three-directional strain gages located.

The mises stress contour plot of six X-joints FE models, as shown in Fig.7 .

Compared the results of experimental test with the computational result of FEA, as shown Fig 8.a-f

4 Parametric study

4.1 Parameters analyse

The FE models provedfeasible by comparing the SCF distribution of FEA with experimental test. Then the research that the influence of each non-dimensional geometricparameters β、2γ、τ and dimensional geometric parameter concrete strength on the distribution of SCF was analyzed by FEA. The practical range of β、2γ、τ and concrete strength were shown in Table 5. The value of concrete strength was added a "hollow", in order to compare concrete-filled with hollow cubular joint. These values in Table 5 refered to API RP2A (1993)[20].

$2a$=1000mm The length of Chord is 1000mm

$2b$=1000mm The length of Brace is 1000mm

t_BThe thickness of Brace

D_BThe Diameter of Brace

t_C The thickness of Chord

D_C The Diameter of Chord

h_fThe welding seam

N=10KN Axial compressive load is 10kN

With 320 groups with different parameters, the FE models were computed and outputted 320 groups of results. These results were all analyzed in the equation of SCF. In FEA, the boundary condition, loading, and material property of steel, mesh size were discussed above.

4.2 The Results Of Parametric Analysis

By using the non-linear regression analysis, the influence of each parameter on SCF has been numerical analysized. Each non-dimension parametric equation include fournon-dimension parameters. These non-dimension parameters as follow, β, 2γ,τ andΔ. The parametersβ, andτ were respective looked as the influences of diameter and thickness of brace on the SCF distribution of joints. And the 2γ looked as the influence of chord thickness on SCF distribution. The parameterΔlooked as the effect of the concrete strength on SCF.

Asβincreases, SCF distribution was increased, both at the chord and brace, as shown in Fig.9 a-b. With the increment of 2γ, SCF distribution was increased, it can be seen in Fig.10 a-b.With the increment of τ, SCF distribution was increased, it can be seen in Fig.11 a-b. The Δ was defined as the grade of concrete divided

5 SCF equation

Each SCF equation contained non-dimension parameters namely β, 2γ, τ andΔ. The influence of these non-dimension parameters on SCF is very complex, as shown in Fig.11-12. By using the SPSS software's non-linear regression analysis, repeat three times, the SCF equations were predicted for CHS-CHS X-joints with concrete-filled brace subjected axial compressive loading, both on chord and brace at the chord and brace intersection.

In the design formulae given in the CIDECT Design Guide No.8 [19]and the API RP2A-WSD [20]for carbon steel tubular X-joints, the SCF equation for the chord crown location in an X-joint subjected axial loading is given as follow:

$$SCF=e^{-0.032}(-0.131\beta^2+0.698\beta+2.839)*\gamma^{1.187}*\tau^{0.037}*\Delta^{-0.012}-3\tau\beta\sin\theta \quad \text{near Brace} \qquad (3)$$

$$SCF=e^{1.300}(-2.120\beta^2+2.127\beta+2.961)*\gamma^{2.014}*\tau^{0.439}*\Delta^{-0.006}-3\tau\beta\sin\theta \quad \text{near Chord} \qquad (4)$$

The scope of β, 2γ,$\tau$and θ as listed below

$0.2\leq\beta\leq1.0$

$15\leq2\gamma\leq64$

$0.2\leq\tau\leq1.0$

$0.5\leq\Delta\leq2$

$30^\circ\leq\theta\leq90^\circ$

Because this paper discussed on the two mutually perpendicular tubular joints, so the parameter θ can be deemed to equal 90. In order to evaluate the effect of concrete strength in SCF equation, Δ=

Based on the SCF equation above, the comparison between the finite element analysis results and the SCF formulae was done in order to prove the SCF formulae. The comparison and finite element analyses of the SCF values of all models obtained from the SCF formulae calculation is shown in Table 6. It exactly proved the SCF formulae calculation fits perfectly with finite element analysis results. Based on the comparison, the statistics of SCF formulae calculation to finite element analysis results ratio were shown in Table 6.

6 Conclusions

In this paper, numerical and experimental researches on the SCF of CHS-CHS X-joints with concrete-filled braces subjected to axial compressive loading were conducted. It can be seen that the newly developed finite element model is reliable. These FE models were used to evaluated the effects of non-dimension geometric parametersβ, 2γ, τandΔon the SCFs of CHS-CHS X-joints with concrete-filled braces subjected to axial loading in brace.

Based on the computational results of 320 finite element models, by using nonlinear regression, two non-dimension parameter equations were fitted. According to these experimental and numerical researches, main concludes contain:

1) The valid and FE model of CHS-CHS X-joints with concrete-filled braces under axial loading on brace was established;
2) The SCF equations of CHS-CHS X-joints with concrete-filled braces under axial loading on brace was derived;
3) A conclusion that the brace filled concrete can decrease the fatigue property of tubular structure was verified.

Acknowledgments

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Table 1 Parameters of X-joints

Specimen number	① $D_C \times t_C$ mm×mm	② $D_B \times t_B$ mm×mm	a (mm)	b (mm)
XBC1	140×4.0	114×3.0	450	350
XBC2	140×4.0	114×2.5	450	350
XBC3	140×4.0	89×2.5	450	350
XBC4	140×4.0	89×2.0	450	350
XBC5	114×2.5	89×2.0	450	350
XBC6	114×3.0	89×2.0	450	350

Table 2Basic material mechanicalproperties

speciman	f_y(N/mm^2)	f_u(N/mm^2)	f_y/f_u	δ(%)
Φ89×2.0	378	445	0.85	21.2
Φ89×2.5	397	480	0.83	19.2
Φ114×2.5	370	448	0.83	26.0
Φ114×3.0	445	565	0.79	18.9
Φ140×4.0	397	462	0.86	18.7

Table 3The estimate loading of X-joints as hollow tubular joint

Joint Number	Reality β	Chord Thickness t(mm)	Chord Yield Strength (MPa)	Bearing Capacity (kN)
XBC1	0.816	3.96	397	100.01
XBC2	0.811	3.88	397	95.00
XBC3	0.632	4.02	397	71.69
XBC4	0.635	4.02	397	71.97
XBC5	0.773	2.74	370	40.51
XBC6	0.770	3.95	445	100.65

Table 4 Boundaries of extrapolation region for CHS joints

<table>
<tr><td colspan="2" rowspan="2">Distance from weld toe</td><td colspan="2">Chord</td><td colspan="2">Brace</td></tr>
<tr><td>Saddle point</td><td>Crown point</td><td>Saddle point</td><td>Crown point</td></tr>
<tr><td rowspan="2">CHS</td><td>$L_{r,min}$</td><td colspan="2">$0.4t_0$</td><td colspan="2">$0.4t_1$</td></tr>
<tr><td>$L_{r,max}$</td><td>$0.09r_0$</td><td>$0.4\sqrt[4]{r_0 t_0 r_1 t_0}$</td><td colspan="2">$0.65\sqrt{r_1 t_1}$</td></tr>
</table>

Table 5 The value of β、2γ、τ and concrete strength

Parameter	Value			
value	0.3	0.5	0.7	0.8
2γ	10	2.	30	40
τ	0.3	0.5	0.7	0.9
concrete strength(MPa)	15	30	45	60
concrete strength(MPa)	Hollow cubular			

Table 6 Comparison of formulae calculation with FEA results for X-joints filled-concrete brace

A total of 256 specimens	Comparison	
	The intersection of the chord side	The intersection of the brace side
Max	2.63	2.46
Min	0.58	0.19
Mean	1.09	1.12
COV	15.52%	12.26%

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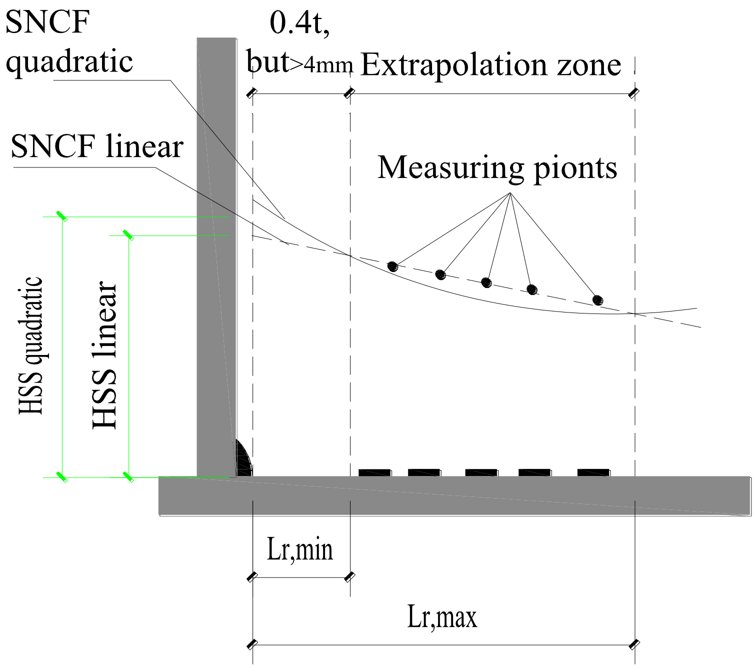


Fig. 1. Definition of extrapolation region

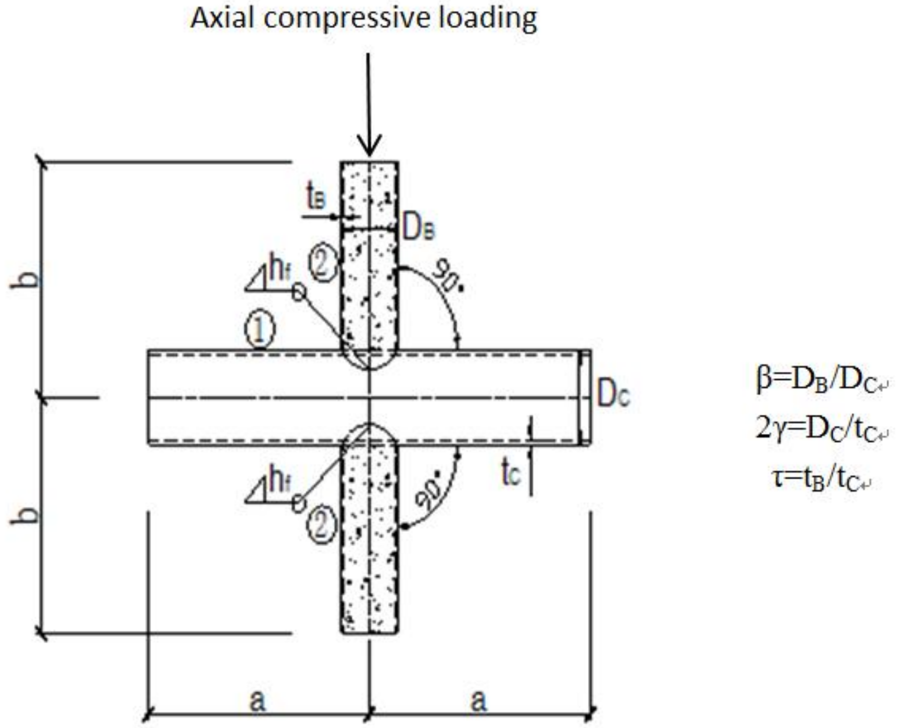


Fig.2. X-joints under axial compressive loading in vertical brace

Fig.2. Photo of specimen joints

Fig. 3. Test equipment

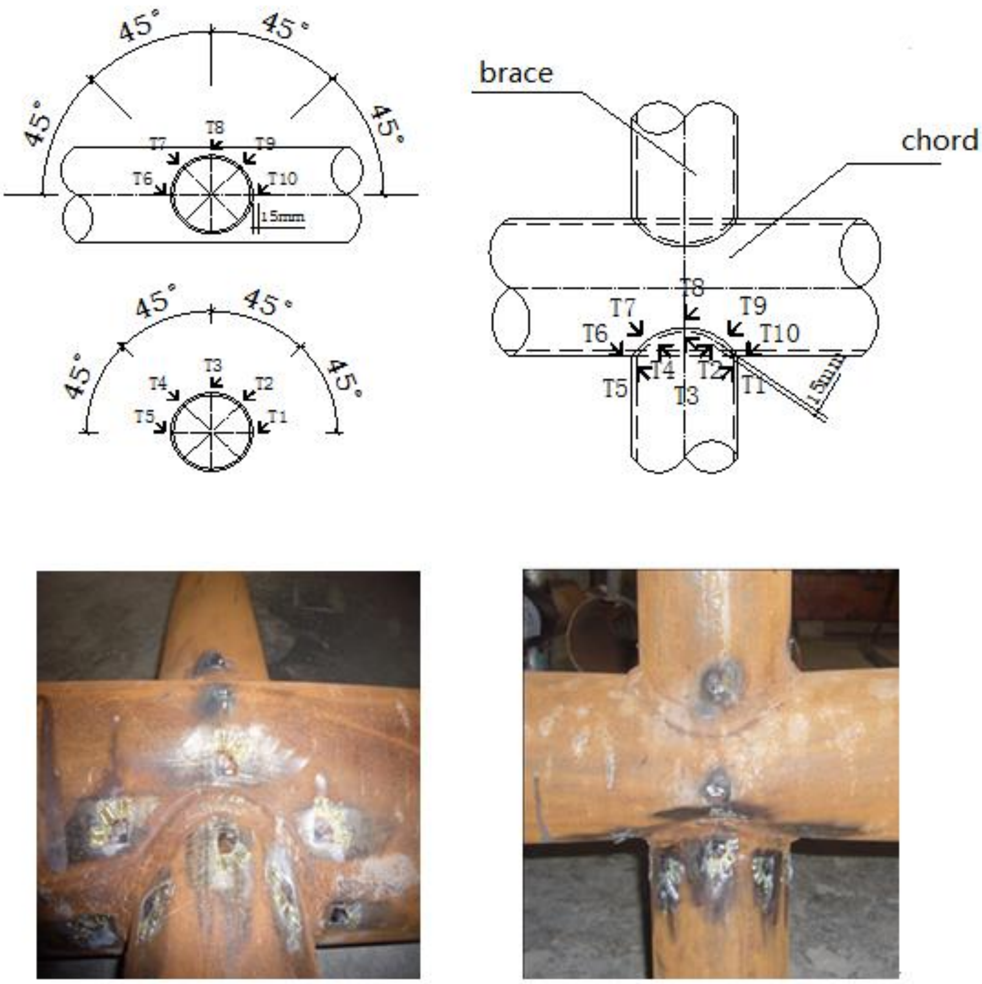


Fig.4. photo of three-direction strain gage

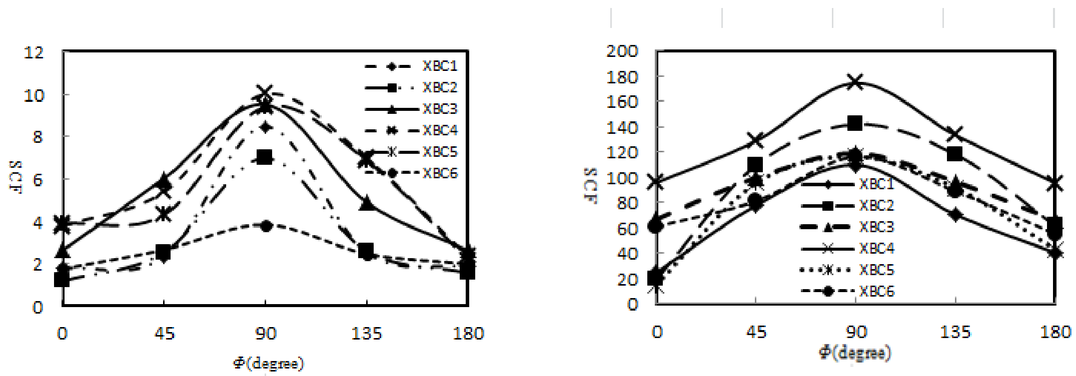


Figure 5 SCF of specimens joint

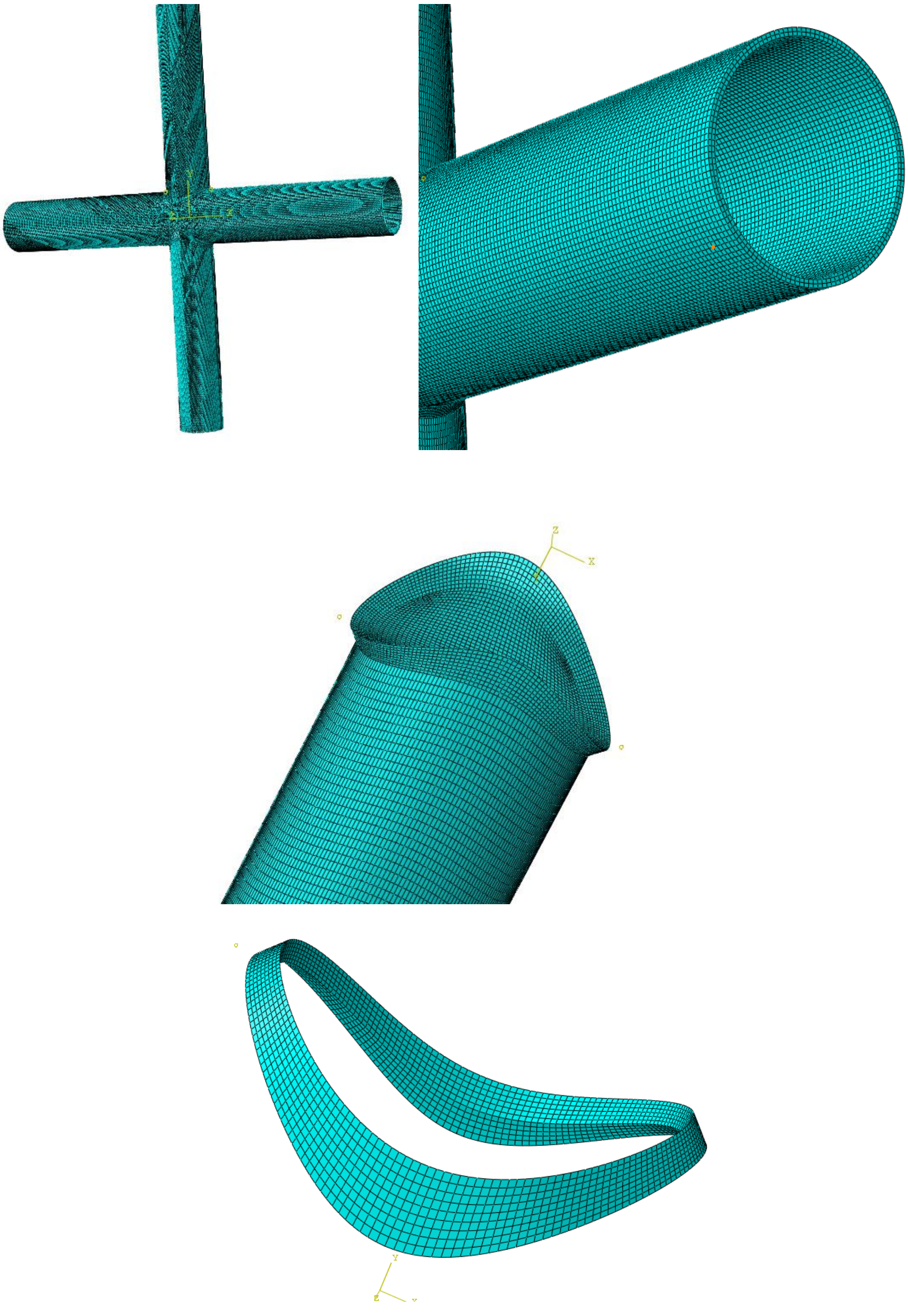


Fig. 6 Mesh of X-joints

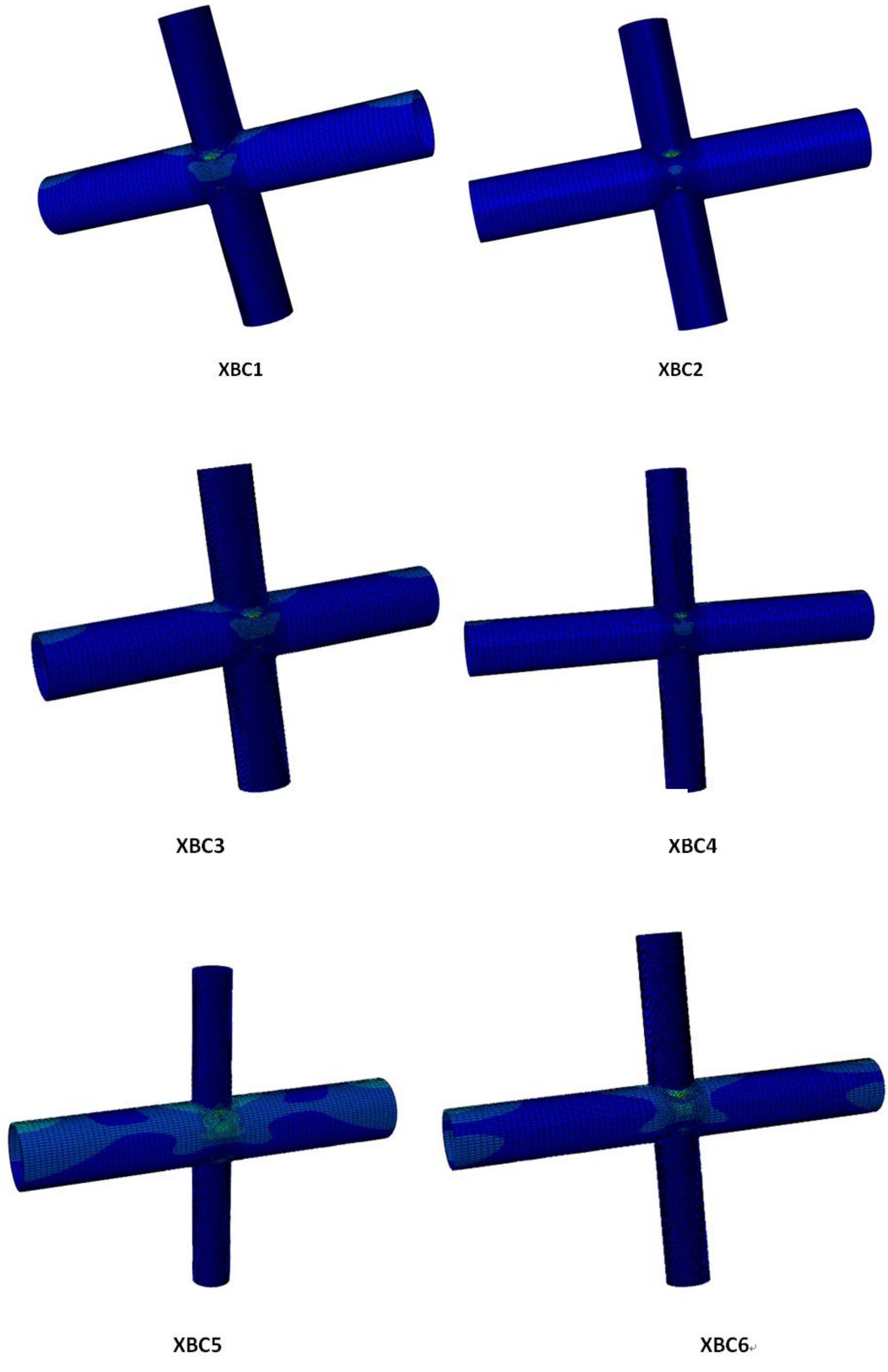
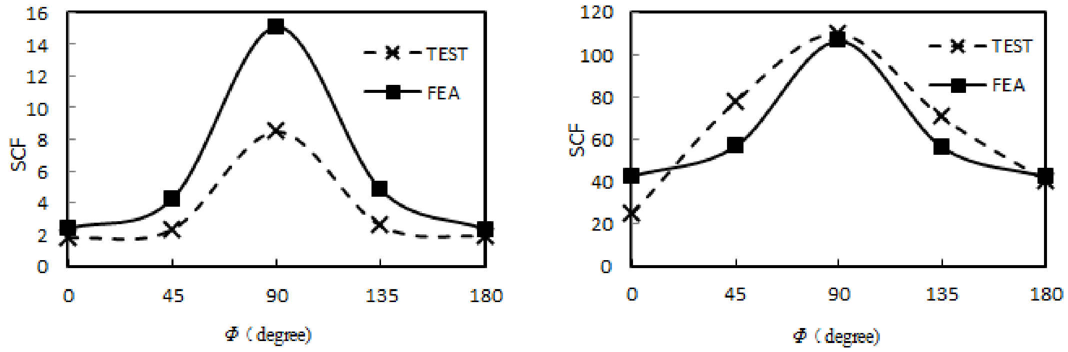
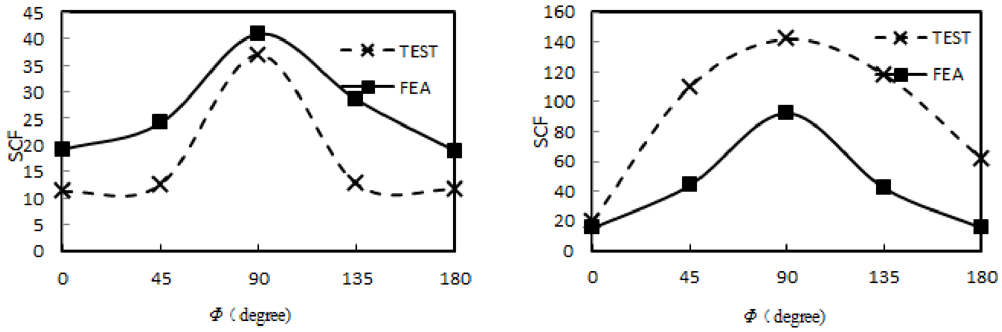


Figure 7 The mises stress contour plot of six X-joints FE models



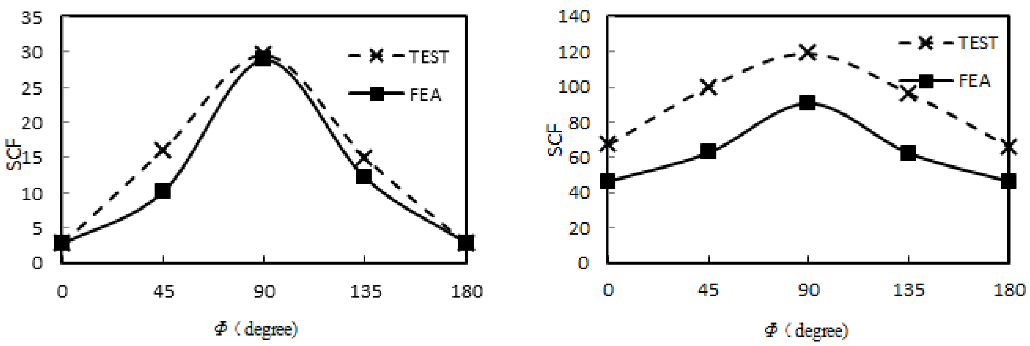
(a)chord and brace intersectionnear brace(b) chord and brace intersectionnear chord

Fig.8-1Comparison of test with FEA SCF for XB1



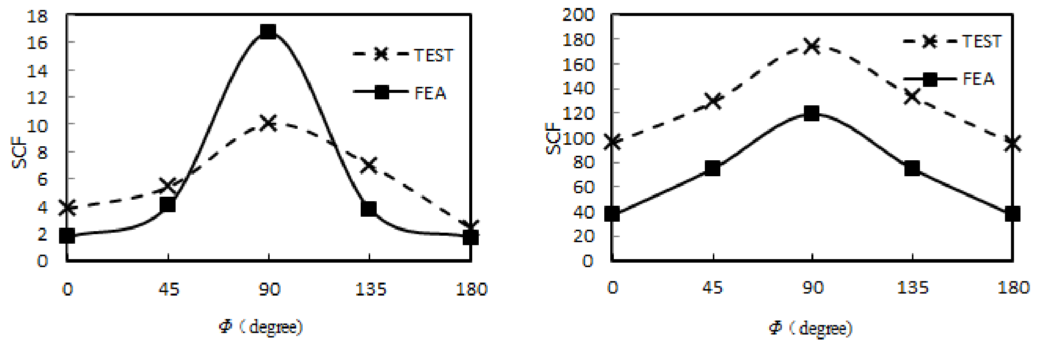
(a)chord and brace intersectionnear brace(b) chord and brace intersectionnear chord

Fig.8-2Comparison of test with FEA SCF for XB2



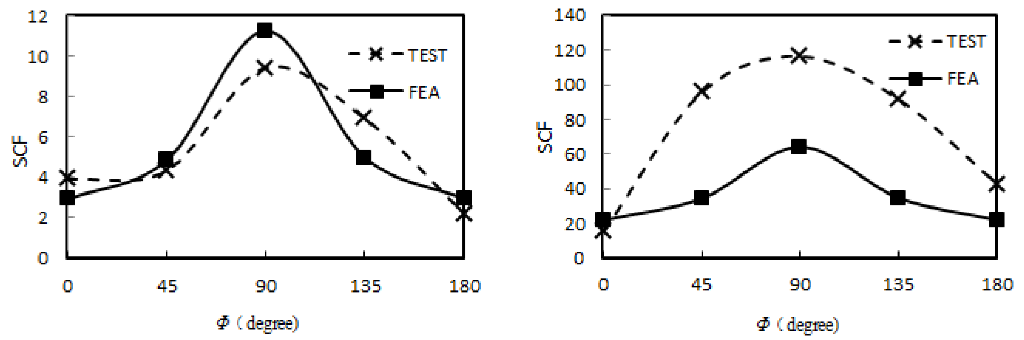
(a)chord and brace intersectionnear brace(b) chord and brace intersectionnear chord

Fig.8-3 Comparison of test with FEA SCF for XB3



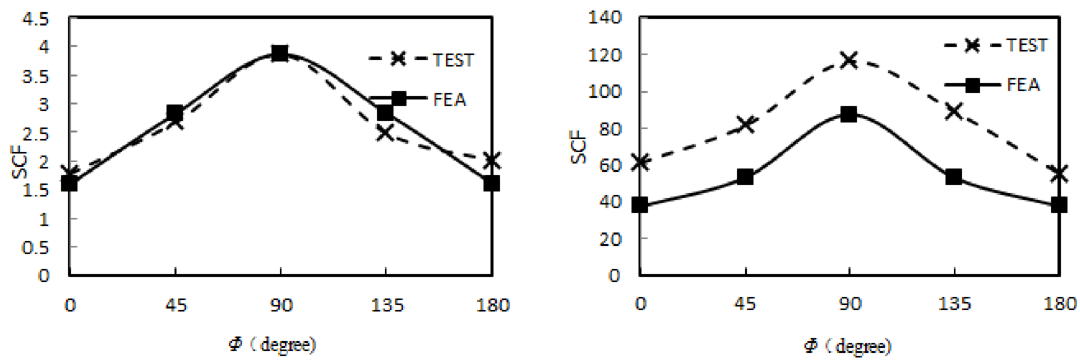
(a)chord and brace intersectionnear brace(b) chord and brace intersectionnear chord

Fig.8-4 Comparison of test with FEA SCF for XB4



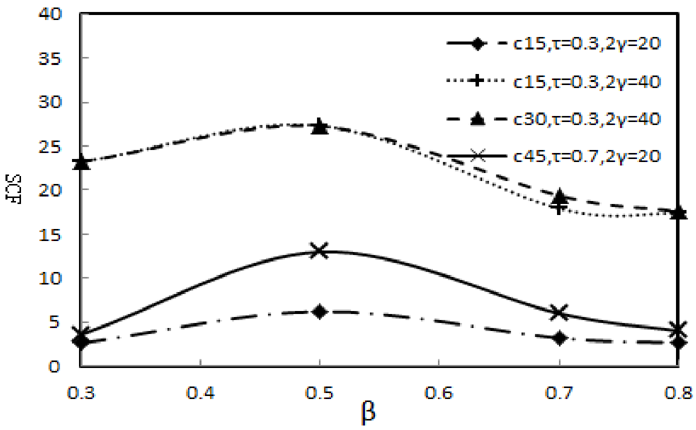
(a)chord and brace intersectionnear brace(b) chord and brace intersectionnear chord

Fig.8-5 Comparison of test with FEA SCF for XB5

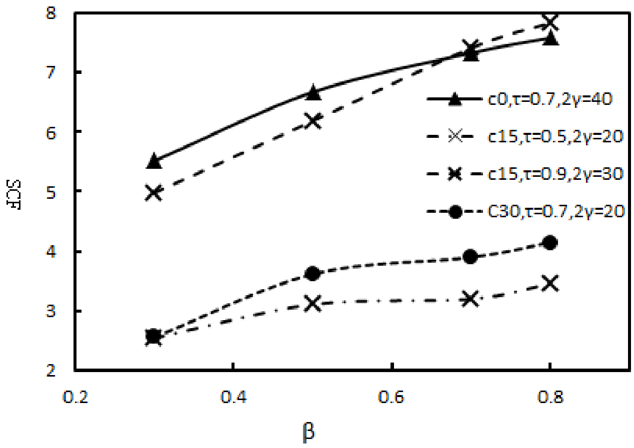


(a)chord and brace intersectionnear brace(b) chord and brace intersectionnear chord

Fig.8-6 Comparison of test with FEA SCF for XB6

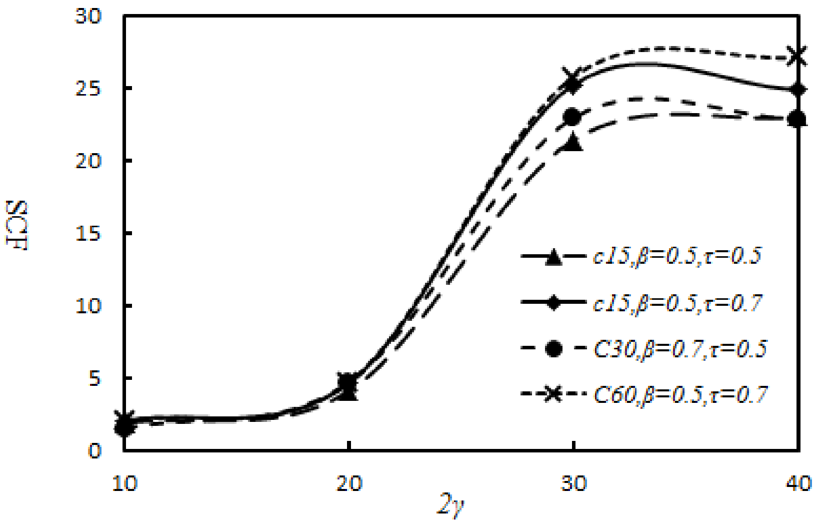


(a) At chord brace intersection(near chord)

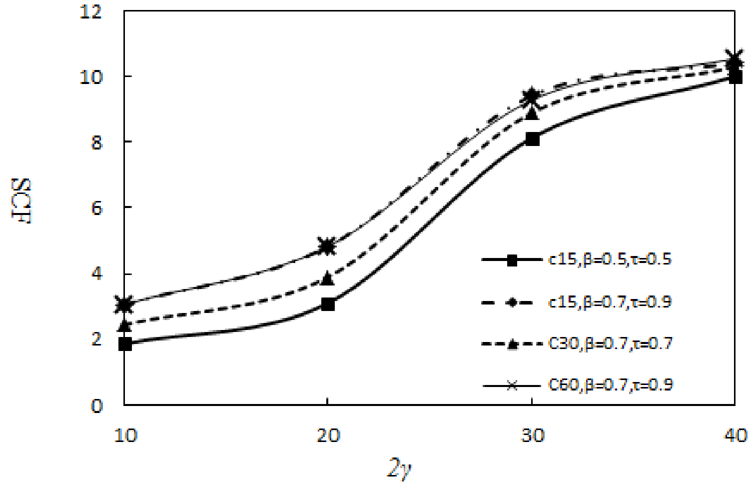


(b) At chord brace intersection(near brace)

Figure 9Curves of SCF-*β*

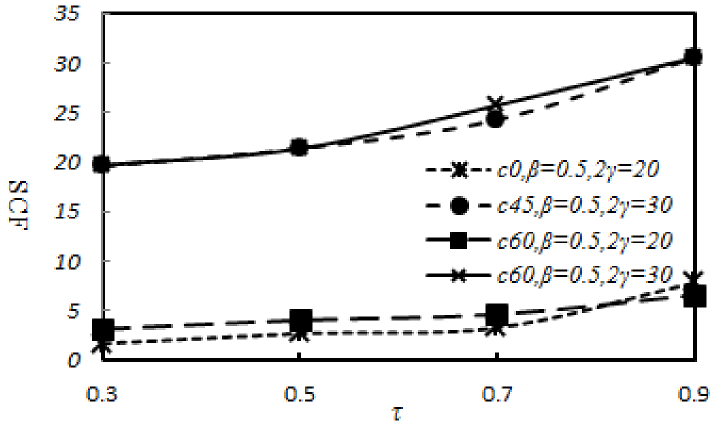


(a)At chord brace intersection(nearchord)

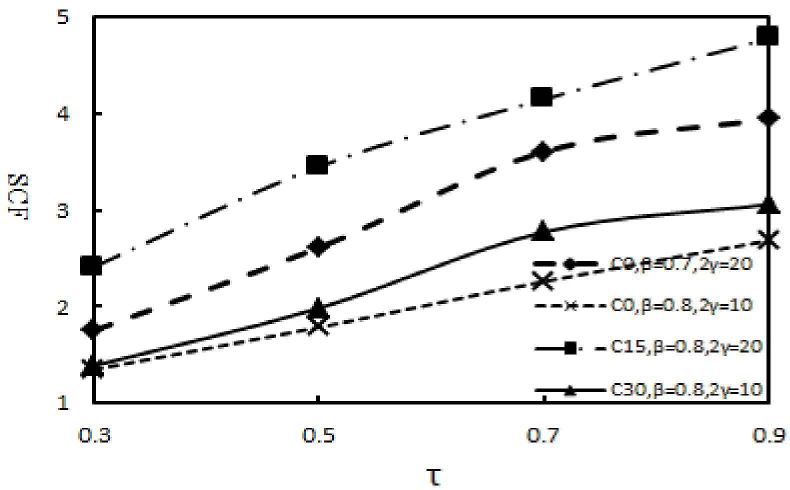


(b) At chord brace intersection(near brace)

Figure 10Curves of SCF-2γ

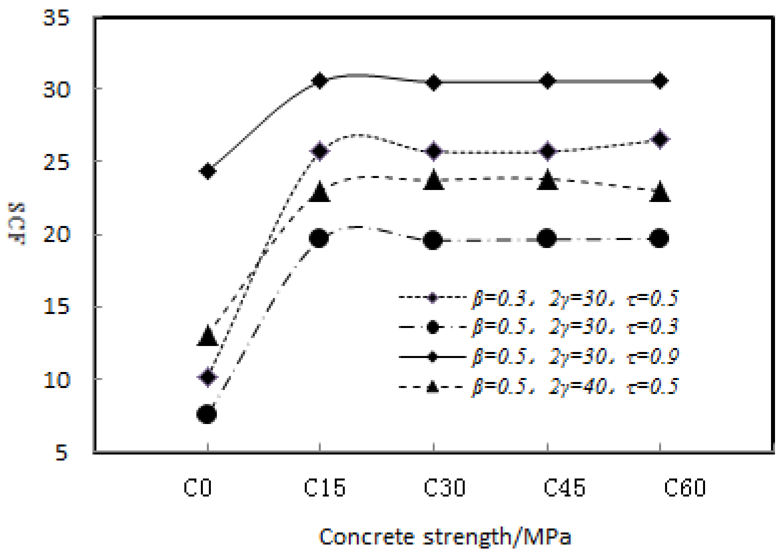


(a) At chord brace intersection(nearchord)

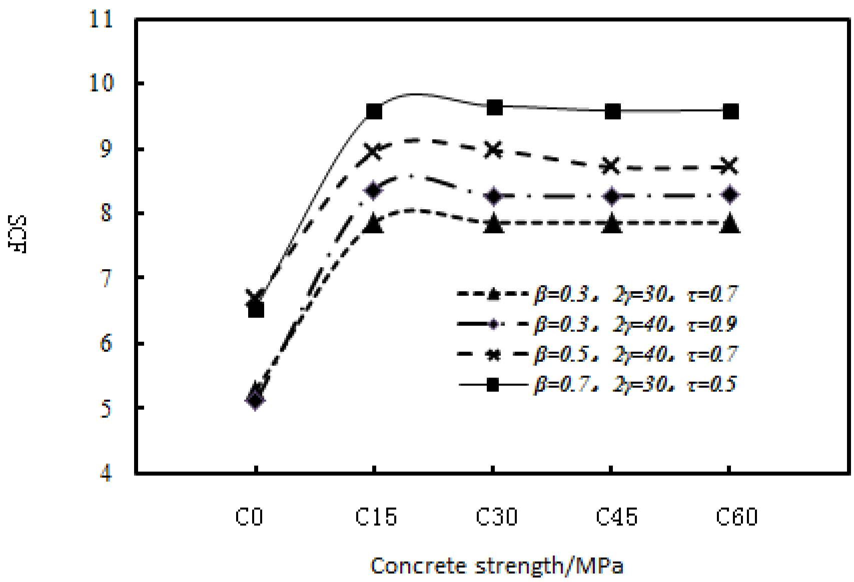


(b) At chord brace intersection(near brace)

Figure 11Curves of SCF-τ



(a) At chord brace intersection(nearchord)



(b) At chord brace intersection(near brace)