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Stress Concentration Factors (SCFs) in Circular Hollow Section CHS-to-H-shaped Section Welded T-Joints under Axial Compression

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Abstract

The aim of this paper is to investigate the effects of non-dimensional geometric parameters on stress concentration factors (SCFs) of circular hollow section CHS brace-to-H-shaped section T-connections under axial compression. This type of welded joints is used increasingly in steel construction. However, its fatigue design is not covered by codes, and its fatigue strength has not been given the deserved attention by researchers. This research, however, bridges the gab on SCFs in this type of welded connections when being loaded in axial compression. here, parametric study based on the numerical analysis was performed to evaluate the effect of CHS brace diameter to H-shaped chord flange width ratio (β), H-shaped chord flange width to thickness ratio (2γ) and CHS brace thickness to H-shaped chord flange thickness ratio (τ) on SCFs in the brace and the chord of the connection. Based on practical considerations, the validity range of these parameters was $0.3 \leqslant \beta \leqslant 0.7$, $16 \leqslant 2\gamma \leqslant 30$ and $0.2 \leqslant \tau \leqslant 0.1$. Three-dimensional finite element (FE) study using commercial software ABAQUS was performed to study the hot spot stress distribution and hence SCFs in this type of welded joints. To begin with, the results of FEM were verified against available experimental data and good agreement was achieved. Afterwards, 48 joints were modeled in Abaqus to study the effect of geometrical parameter on SCFs in brace and chord. Based on the results of this extensive study, the effect of geometrical parameters was revealed. The paper, thus, shows that whilst β increases, SCFs in the brace and chord increases. Moreover, increasing the parameter 2γ results in an increase in SCFs in the two members. However, the change in τ has no significant effect on the SCFs in the brace or the chord. Values of SCFs are found to be between 2 and 7.

Keywords: SCFs; Fatigue desig; Welded connections; H-shaped; CHS sections.

1. Introduction

Steel hollow sections are being extensively used in steel construction due to their excellent performance. They are widely used in many engineering applications like power transmission columns, bridge engineering, industrial buildings and offshore structures [1]. In addition to their good structural behaviour, they have attractive aesthetic appearance. Specific type of welded joints is formed by welding circular hollow section (CHS) brace-to-H-shaped chord as shown in Figure 1. The use of such members is being increasingly used in steel construction because it has many advantages over the conventional CHS-to-CHS sections. For example, the use of H-shaped chord would provide flat surface so that purlins and sheeting could be properly installed. Moreover, the fabrication efforts are much lower in this type of connections because of flat plane provided by the flange of the H-shaped chord.

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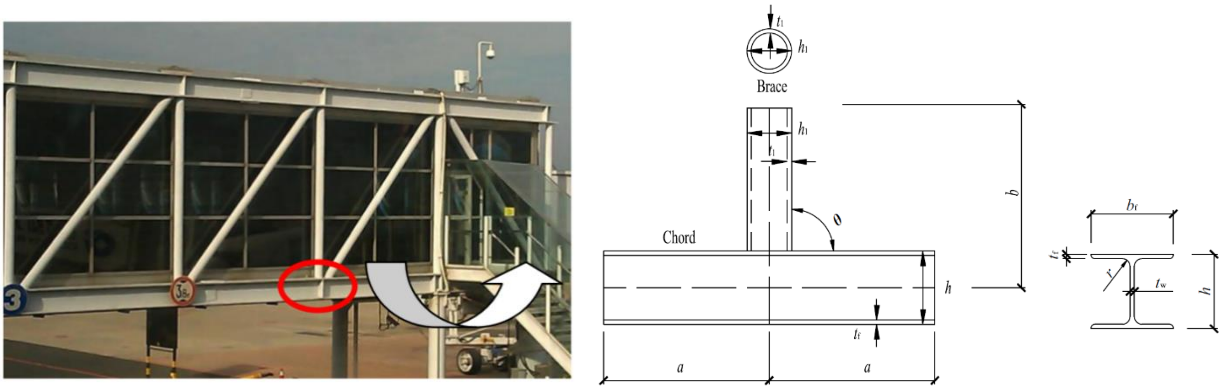


Figure 1. CHS brace to H-section chord joint [23]

The fatigue failure of welded joints is considered as a main concern in steel structures, especially when joints are being subjected to repetitive or cyclic loadings like seismic or wind loadings. Fatigue failure need not necessarily to be caused by large loadings, however, it can be initiated by repetitive applications of small loads. Therefore, it is very important to study the fatigue performance of welded joints for proper design. The fatigue design of such joints is not governed by their static design. Yet, there are many methods used to study fatigue behaviour of welded joints; on of which is the hot spot stress method (presented briefly in section 3) is the most commonly used one. The fatigue life of welded joint is related to the stress concentration around at the intersection of brace and chord. Initiation of cracks due to repetitive loadings is caused by hot spot stresses (or geometrical stresses) that are caused by the presence of geometrical discontinuities like weld toe. Therefore, fatigue cracks is always initiated around the weld toe of the brace or chord of a joint.

A review of the available literature reveals that extensive research studies have been done so far on the fatigue failure of different types of welded joints with different configurations. For example, Ummenhofer et al. [2] conducted experimental studies to investigate the extension of the fatigue life of existing and new welded hollow section joints. Also, Feng and Young [3] proposed parametric equations based on experimental and numerical studies to describe SCFs in the brace and chord of the cold-formed stainless-steel tubular X-joints. The fatigue behaviour of CHS-to-RHS T-joints under both axial loading and in-plane bending have also been studied experimentally by Bian and Lim [4]. Parametric formulas to describe SCFs for the fatigue analysis of K-joints have been proposed by Ahmadi and Asoodeh [5] as a result of comprehensive study performed using finite element method (FEM). Furthermore, Ahmadi and Lotfollahi-Yaghin [6] have analyzed KT-joints using FEM to study SCFs due to in-plane bending loads. New types of welded joints like square bird-beak and diamond bird-beak SHS-to-SHS joints were also investigated both experimentally and numerically [7-12]. Because of the many benefits gained by the combined action of steel and concrete, concrete filled tubes CFT have been increasingly used in many engineering applications [13-15]. Numerous studies have demonstrated the effectiveness of using concrete-filled members in reducing stress concentrations and enhancing the fatigue life of welded joints [16-21]. The static strength of CHS brace-to-H-shaped chord X-joints under in-plane bending was studied by Feng et al. [22]. Moreover, the static strength of CHS brace-to-H-shaped chord T-joints was investigated by Feng et al. [23].

The results of the above mentioned research reveal that no research studies have been conducted on the fatigue behaviour of CHS brace-to-H-shaped chord joints under axial compression. While there is a limited research available on the static behaviour of such joints under axial compression and in-plane bending [22-23], these studies were not performed to study SCFs or the fatigue behaviour. They were only directed toward the assessment of the joint static strength. So, up to the author's knowledge, no experimental or numerical studies have been done so far to evaluate SCFs in CHS-to-H-shaped joints under axial compression. Therefore, this finite element study seeks to determine SCFs in the brace and the chord. To ensure the safety of steel structures which contains such joints, SCFs need to be accurately reported to design against fatigue failure. It is not practical to do experiments which are time and cost consuming by designers. As such, extensive numerical study has been performed in this paper to determine SCFs so that results could be used by engineers to design against fatigue damage. The results obtained in the research will help in determining hot spot stresses which will be used with S-N curves to predict the fatigue life of the welded joint.

2. Research Methodology

The following points illustrate the methodology I followed throughout doing this research:

1. The experimental fatigue behaviour of circular hollow section CHS brace-to-H-shaped brace T-connections under axial compression is not well established in literature and there are no experimental data available on SCFs in CHS brace or H-shaped chord for this type of connections. So, to verify finite element models prepared in Abaqus, similar welded joints available in literature have been modelled and analysed in Abaqus and good

agreement was achieved. The details of verification models and the corresponding experiments are presented in section 4.5.

2. Afterwards, finite element models for the CHS brace-to-H-shaped chord T-connection under axial compression were prepared in Abaqus. The details of the FE models are clearly shown in section 4. Steel material properties are 200 GPa and 0.3 for the Young's modulus and Poisson's ratio, respectively. Moreover, linear elastic analysis was considered based on recommendations from previous research. The element type and extrapolation method for extraction of FE results are well-demonstrated in sections 4.1 and 4.2.
3. Parametric study was performed where 48 joints were considered to account for the effect of the non-dimensional geometric parameters on SCFs in brace and chord. The parameters considered are: CHS brace diameter to H-shaped chord flange width ratio (β), H-shaped chord flange width to thickness ratio (2γ) and CHS brace thickness to H-shaped chord flange thickness ratio (τ).
4. Results were tabulated and the relationships between each parameter and SCFs were drawn and presented in section 5.

3. Hot Spot Stress Method

The hot spot stress method is the most commonly used method to design fatigue life in welded joints. SCF is defined as the ratio of hot spot stress to nominal stress. Owing to the geometrical discontinuities near the weld bead, nominal stresses are usually magnified. It is believed that geometrical configuration of a joint greatly affects stress distribution and hence SCFs in welded joints. Many factors like depth, width and thicknesses of the chord and brace, besides the weld size, seriously affect SCFs. For the ease and effectiveness of doing parametric studies, such factors are usually expressed in terms of non-dimensional geometric parameters. The main parameters considered in this study are the brace diameter to the cord width (β), the chord width to its thickness (2γ), and the brace to the chord thicknesses ratio (τ). The details of the parametric study performed in current paper are presented in section 4.

4. Finite Element Analysis

Stress concentration factors (SCFs) are usually investigated both experimentally and numerically. However, due to time and expensive costs of doing experiments, the finite element method (FEM) represents a powerful numerical method that can be successfully used to evaluate SCFs in various types of welded joints. The commercial general-purpose finite element software ABAQUS [24] has been employed in the current study to examine the effects of non-dimensional parameters on SCFs in the chord and the brace.

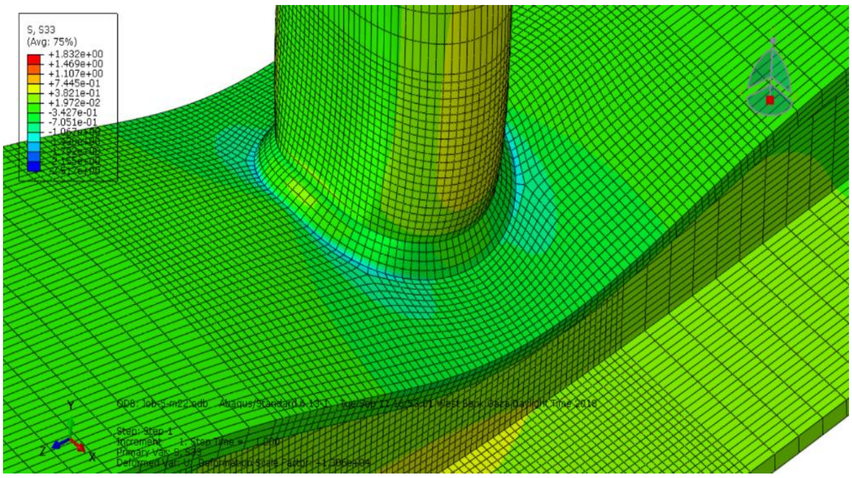


Figure 2. Mesh refinement around the weld bead

4.1. Element Type and Mesh Size

The element type, integration scheme and mesh refinement have great impact on SCFs around the weld bead. The connection has been partitioned in ABAQUS to allow the use of three-dimensional 20-noded quadratic solid elements with reduced integration scheme 2 x 2 x 2 (C3D20R). The use of C3D20R elements was shown to be the best element type for SCFs determination in welded joints [25].

Mesh refinement is adopted at the intersection between the CHS brace and the H-shaped chord for accurate prediction of stress variations. Besides, three layers of solid elements were provided through the thickness of the upper flange of the chord and the thickness of the brace (see Figure 2).

4.2. Material Properties and Analysis Type

Linear elastic analysis is used since it was shown that the use of such analysis gives accurate results for SCFs in steel welded joints [5, 26-27]. Young's modulus and Poisson's ratio were set to 200 GPa and 0.3, respectively for all elements of the connection including weld bead.

4.3. Loading and Boundary Conditions

Since the study aims at investigating SCFs under axial compressive loading, compressive pressure of 1 MPa is applied to the CHS brace. The application 1 MPa is chosen so that nominal stress is 1 MPa and hence SCF at a node equals the hot spot stress at that location. Pinned boundary condition is assigned at both ends of the H-shaped chord member as shown in Figure 3.

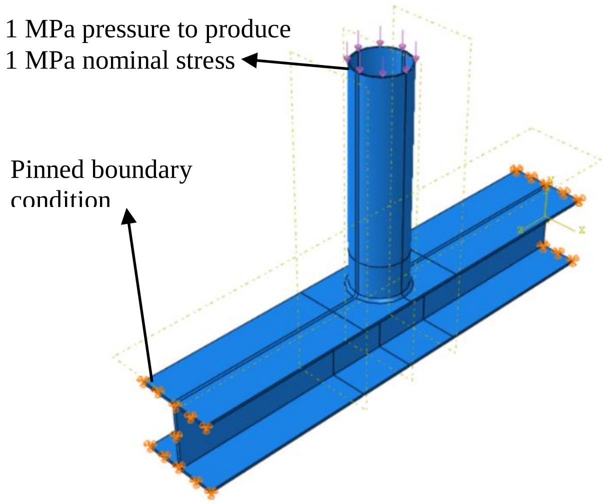


Figure 3. Axial compressive load of 1 MPa applied at the CHS brace. Pinned boundary conditions applied at the two ends of the H-shaped chord

4.4. Extraction of SCFs from FEM models

Stresses perpendicular to weld toe are considered as the hot spot stresses based on the work and recommendations of many researchers [22, 25, 28]. Due to the presence of weld toe, stresses are being largely magnified. To exclude stress concentration due to welding fabrications and local weld toe, design codes like CIDECT [29] recommends extrapolation procedures for extraction of SCFs. Two methods are recommended for extrapolation; linear and quadratic. The latter one is recommended for square hollow sections SHS and rectangular hollow RHS sections because of strong nonlinear stress variation. On the other hand, linear extrapolation is recommended for CHS. In this study, quadratic extrapolation is adopted for getting SCFs. Figure 4 presents extrapolation distances recommended by CIDECT for extrapolation. For quadratic extrapolation, the first value is recommended to be 0.4t from the weld toe but not less than 4 mm and the final point is 1.0t measured from the first point.

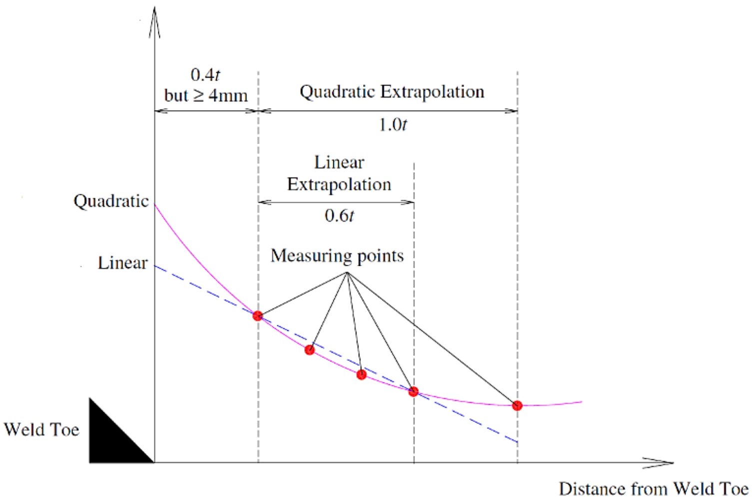


Figure 4. Methods of extrapolation from the weld toe [3]

4.5. Verification of Finite Element Model

Literature review presented in the introduction reveals that no experimental results are available on SCFs in CHS brace-to-H-shaped joints under axial compression. Therefore, verification of FE modelling is made by a comparison with SCFs from experiments available in literature on similar welded joints. The details and the development of FE verification models are presented in [30], however, a brief description is presented here for completeness. Ten joints (one CHS-to-CHS joint, one CHS-to-RHS joint and eight RHS-to-RHS joints) were modelled using ABAQUS for verification. The details of the experimental procedures of CHS-to-CHS, CHS-to-RHS and RHS-to-RHS joints are presented in [2] and [4] and [25], respectively. FE models for these joints are presented in Figures 5, 6 and 7. A refined mesh is used around the weld. Figure 8 [30] presents the results of the mesh sensitivity study performed to select the best element size when doing FE analysis in Abaqus. This study was performed for the CHS-to-CHS joint and it was shown that choosing element size of around 3 mm or a smaller size would result in acceptable values of SCFs with an error percent less than 7%. It is important to note that all modelling procedures and method of analysis used for the verification models are exactly as those outlined in finite element analysis (section 3). Table 1 presents a comparison between FE SCFs and experimental SFCs for all models considered for verification. It can be seen from Table 1 that the results of FE models are in good agreement with experimental results.

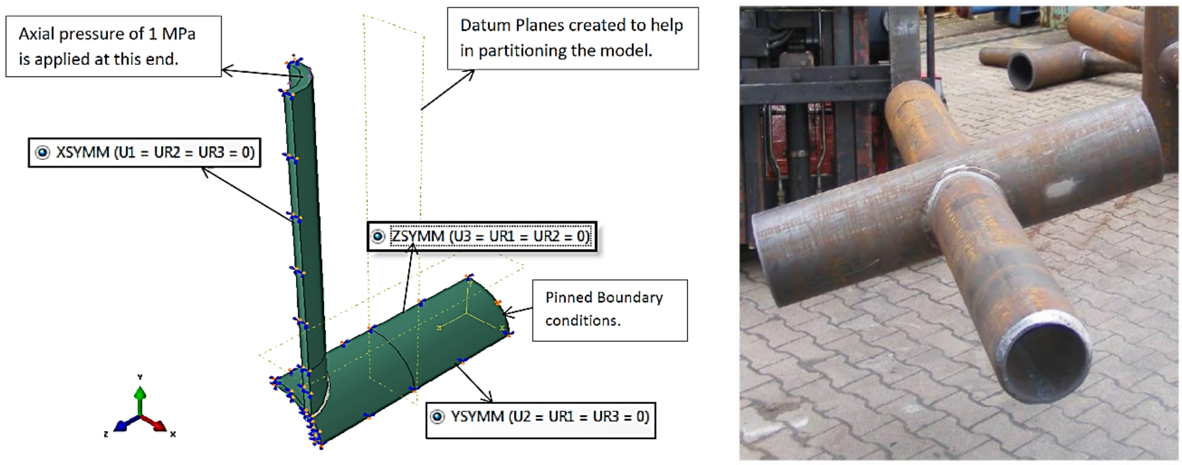


Figure 5. (a) FE validation model of CHS-to-CHS connection [30]. (b) Experimental setup of the CHS-to-CHS joint [2]

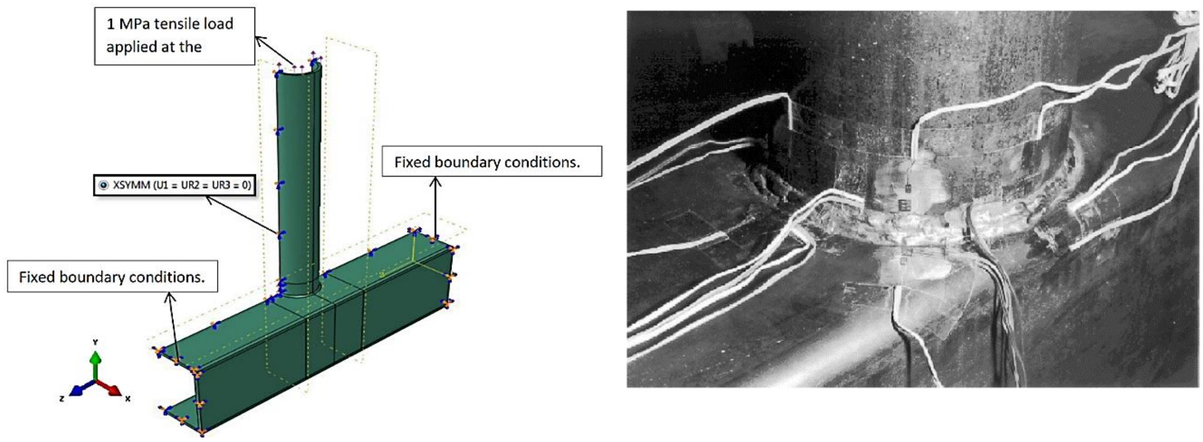


Figure 6. (a) FE validation model of CHS-to-RHS connection [30]. (b) Experimental setup of the CHS-to-RHS joint [4]

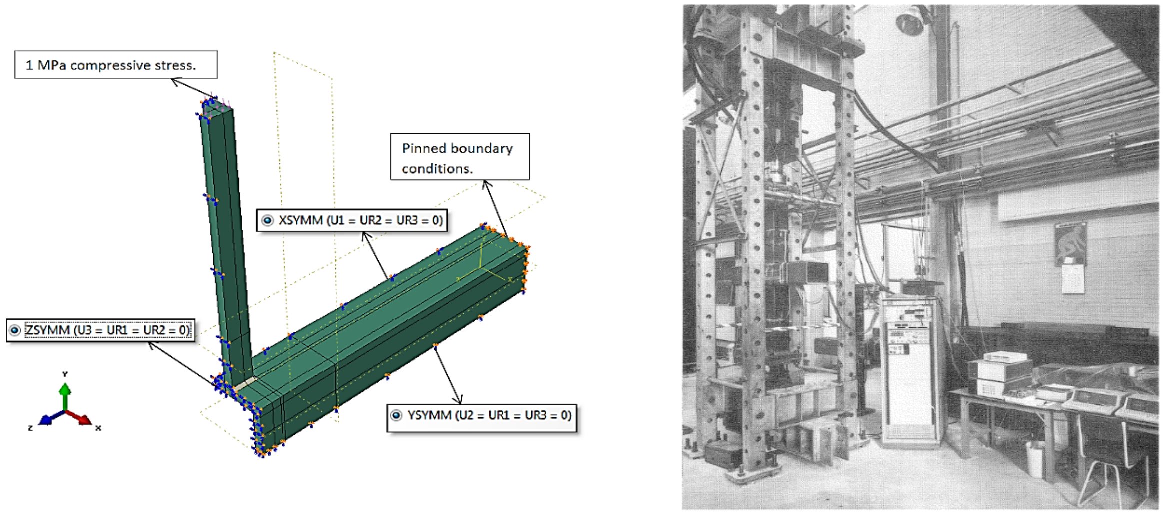


Figure 7. (a) FE validation model of RHS-to-RHS connection [30]. (b) Experimental setup of the RHS-to-RHS joint [25]

Table 1. Comparison between FE SCFs and experimental SCFs for all verification models.

Joint	FE SCFs	Exp. SCFs	Error%
RHS-to-RHS-1	9.62	9.9	3%
RHS-to-RHS-2	11.93	11.96	0%
RHS-to-RHS-3	10.82	10.27	5%
RHS-to-RHS-4	7.01	6.44	9%
RHS-to-RHS-5	7.87	7.34	7%
RHS-to-RHS-6	8.44	8.9	5%
RHS-to-RHS-7	7.89	7.85	1%
RHS-to-RHS-8	5.79	5.18	12%
CHS-to-CHS	4.77	4.67	2%
CHS-to-RHS	14.05	14.3	2%

5. Parametric study

To investigate the effect of the non-dimensional geometric parameters on maximum SCFs in CHS brace-to-H-shaped section joint, parametric study was performed. Three parameters have been considered in this study: the brace diameter to the cord width (β), the chord width to its thickness (2γ), and the brace to the chord thickness ratio (τ). A total of 48 joints have been carefully analyzed with parameters range (β=0.3-0.7, 2γ=16-30 and τ=0.3-1.0) as presented in Table 2. These ranges were selected to reflect corresponding values used in practical applications. This was done to exclude the effect of boundary conditions on SCFs. In all models considered in the parametric study, the chord depth, width and web thickness have been taken to be 200 mm, 200 mm, and 8 mm, respectively.

5.2. Results of Parametric Study

Stresses perpendicular to the weld toe are considered are the maximum stress to be used for calculations of SCFs. Here, S22 and S33 are regarded as the stresses perpendicular to the weld toe in the brace and chord, respectively. The results of the parametric study clearly show that SCFs in CHS brace are generally larger than the SCFs in H-shaped chord. Therefore, the initiation of cracks is expected to occur first in the CHS brace. Figure 9 shows the maximum stress SCFs in the brace and the chord for all 48 models under axial compression. SCFs in the chord are larger than the corresponding ones in the brace. This is due to the shape of the H-shaped chord compared to the more uniform shape of the CHS brace. Moreover, SCFs measured in brace of the majority of models were less than 2. However, higher SCFs are noticed in the H-shaped chord where values were measured to be ranging from 2 to 6.8. Due to symmetry of the joint, symmetrical stress distribution is noted around the weld. The distribution of angles around the weld bead is illustrated in Figure 10, in which, angles were distributed in increasing order clockwise from zero to 360 degrees to indicate the position of maximum SCF in the brace and the chord. Figures 11 and 12 present hot spot stress distribution and hence SCFs distributions around the weld bead in the CHS brace and H-shaped chord at eight different angles (0, 45, 90, 135, 180, 225, 270 and 315) degrees as shown in Figure 10. Figures 11 and 12 clearly show the symmetrical SCFs distributions around CHS brace and H-shaped chord. Angles of zero and 180 are the expected locations of maximum stress concentration in the CHS brace as shown in Figure 13 where contour map of stresses perpendicular to weld toe are presented. So, the maximum SCF in the CHS brace was about 3.25 at angle 0 and 180. For the H-shaped chord, maximum stress concentration is expected to occur at four angles; 45, 135, 225 and 315 as shown in Figures 12 and 14 (where contour map of stresses perpendicular to the weld toe is presented). The blue colors in Figures 13 and 14 shows the locations of maximum stresses perpendicular to the weld toe in CHS brace and H-shaped chord, respectively. Therefore, SCFs in brace and chord are measured at these locations for all models considered in this study. The maximum SCF occurs in the brace for β=0.7, 2γ=30 and τ=1.0 with a value of 6.8. According to CIDECT, SCF may be considered 2 whenever a SCF is recorded with a value less than 2. The effects of geometric parameters on SCFs are discussed in the following sections.

Table 2. Results of parametric study

Model No.	β	2γ	τ	SCF_{chord}	SCF_{brace}	model No.	β	2γ	τ	SCF_{chord}	SCF_{brace}
1			0.3	0.3	1.9	**24**		20.0	1.0	2.2	4.36
2		16.0	0.5	1	2.5	**25**			0.3	0.77	3.01
3			0.8	1.2	2.8	**26**		25.0	0.5	1.24	3.72
4			1.0	1.4	3	**27**			0.8	1.55	4.21
5			0.3	0.5	1.9	**28**	0.5		1.0	1.7	4.87
6		20.0	0.5	0.8	2.5	**29**			0.3	0.76	3.4
7			0.8	0.9	2.3	**30**		30.0	0.5	1.3	3.83
8	0.3		1.0	1.2	2.6	**31**			0.8	1.52	4.34
9			0.3	0.51	2.3	**32**			1.0	1.93	5.34
10		25.0	0.5	1.27	2.64	**35**		16.0	0.8	2.65	5.04
11			0.8	0.99	3.3	**36**			1.0	3.6	5.35
12			1.0	1	3	**37**			0.3	1.05	3.1
13			0.3	0.5	2.25	**38**		20.0	0.5	1.51	3.2
14		30.0	0.5	0.66	2.69	**39**			0.8	1.93	4.62
15			0.8	0.97	3	**40**			1.0	2.08	5.1
16			1.0	0.7	3.5	**41**	0.7		0.3	1.1	3.1
17			0.3	0.72	2.5	**42**		25.0	0.5	1.23	3.33
18		16.0	0.5	1.32	3.11	**43**			0.8	2.45	4.27
19			0.8	1.86	4.26	**44**			1.0	2.63	5.89
20	0.5		1.0	2.78	4.42	**45**			0.3	1.15	3.2
21			0.3	0.72	2.7	**46**		30.0	0.5	1.29	3.25
22		20	0.5	1.24	3.35	**47**			0.8	1.77	5.51
23			0.8	1.75	4.54	**48**			1.0	1.65	6.8

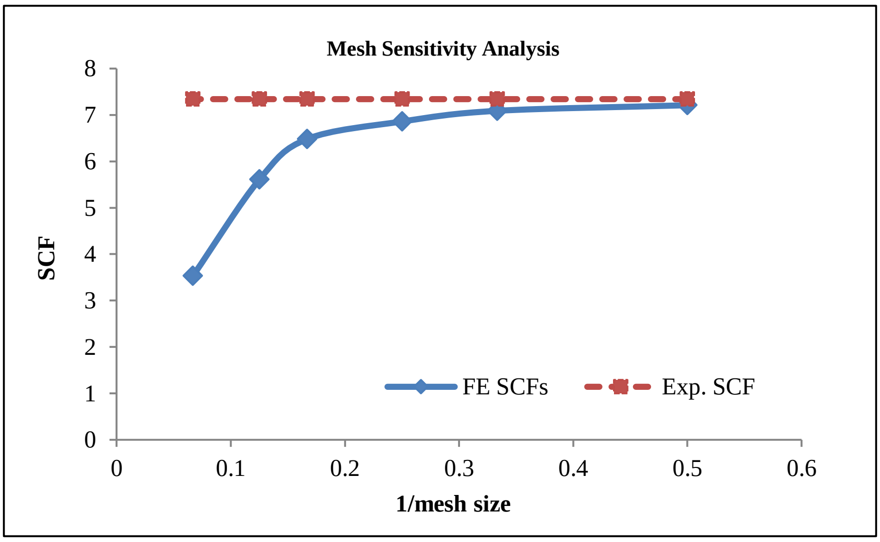


Figure 8. Sensitivity study to select the best element size for validation model [30]

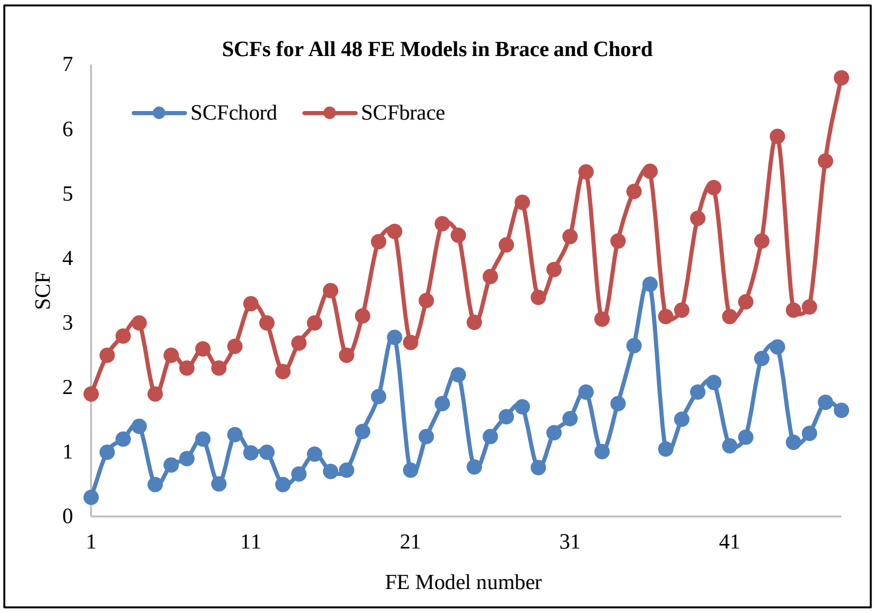


Figure 9. A comparison between SCFs in brace and chord

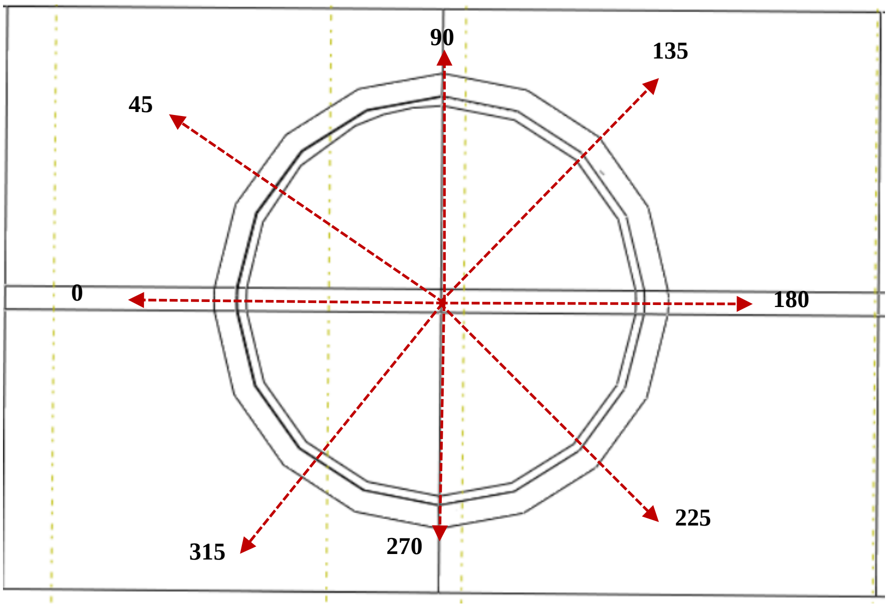


Figure 10. Angle around the weld bead

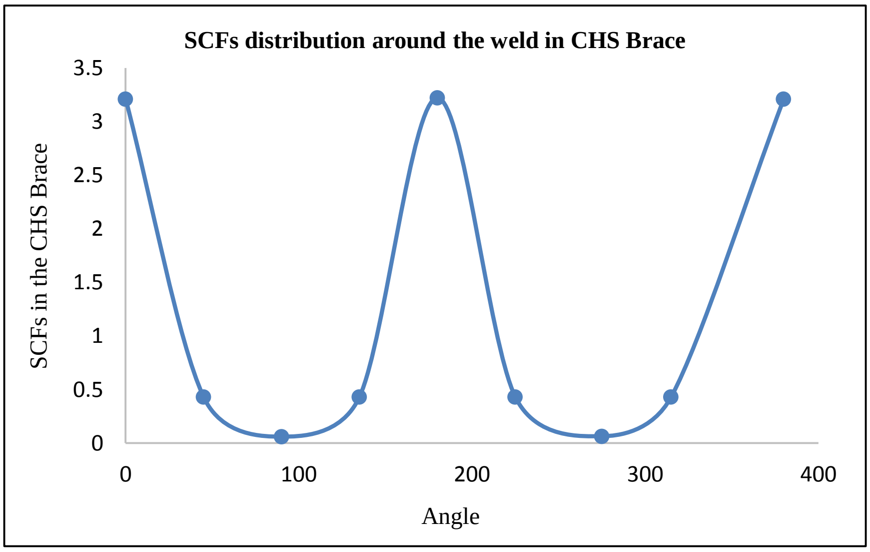


Figure 11. SCFs distribution around the CHS brace

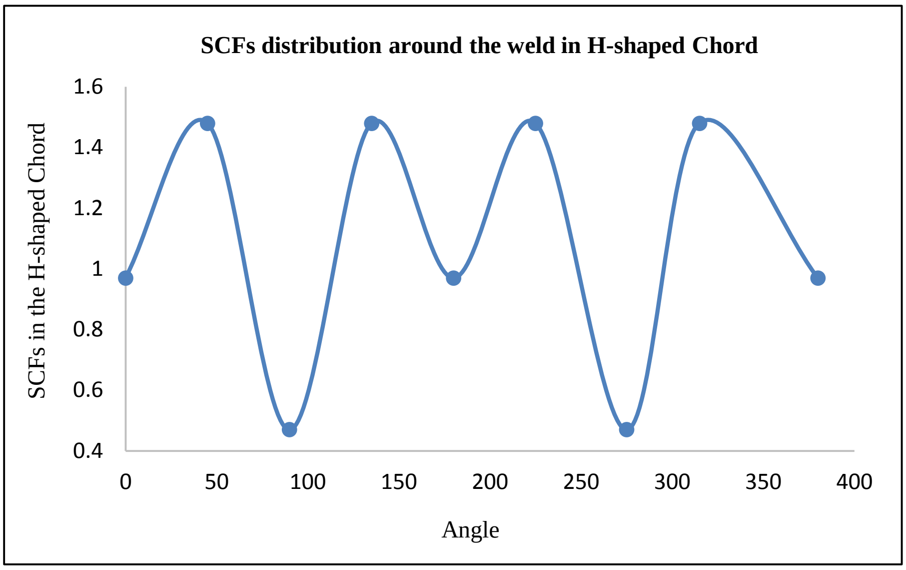


Figure 12. SCFs distribution around the H-shaped chord

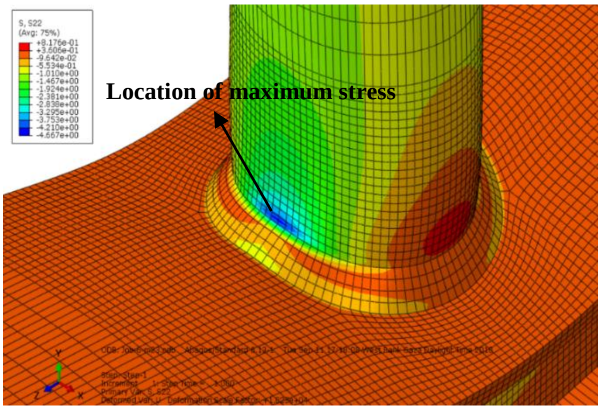


Figure 13 maximum stress perpendicular to the weld toe in the CHS brace

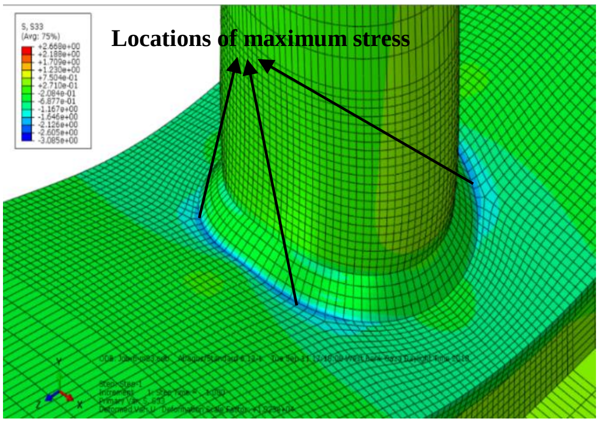


Figure 14 maximum stress perpendicular to the weld toe in the H-shaped chord

5.3. Effect of CHS Brace Thickness to H-Shaped Chord Flange Thickness Ratio (τ)

The range of the parameter τ is [0.2-1.0]. For all models, the H-shaped chord's flange thickness is kept constant. So, increasing τ results in an increase of wall brace thickness. Figure 15 shows the effect of changing the brace wall thickness to H-shaped upper flange thickness on SCFs in the brace and chord for different values β (0.3, 0.5 and 0.7) and 2γ (16, 20, 25 and 30). As it can be noted from Figure 15, increasing the parameter τ would gradually increase the SCFs in the brace and the chord. The maximum SCFs in the brace or chord occurs when τ = 1 (when the CHS wall and the H-shaped chord upper flange thicknesses are equal). The maximum SCFs in the brace under axial compression generally result when the parameter 2γ is 30.

5.4. Effect of CHS Brace Diameter to H-Shaped Chord Flange Width Ratio (β)

The range of the parameter β is [0.3-0.7]. As β increases, the brace diameter increases because the H-shaped chord is kept constant in all models. β is one of the most influential parameters on SCFs in brace and chord. As β increases, SCFs greatly increase in the CHS brace and the H-shaped chord. Figure 16 presents the variation of SCFs in brace and chord due to the increase in β for different values of τ (0.3, 0.5, 0.8 and 1.0) and 2γ (16, 20, 25 and 30). Since values of SCFs shown in Figures 15 (e) and 15 (f) are smaller than 2, SCFs can be conservatively considered as 2. It can be seen from Figure 15 that the maximum SCFs occurs when the parameter β is 0.7. It is interesting to note that for β = 0.3, SCFs are less than 1.5, therefore, conservative value of 2 could be considered.

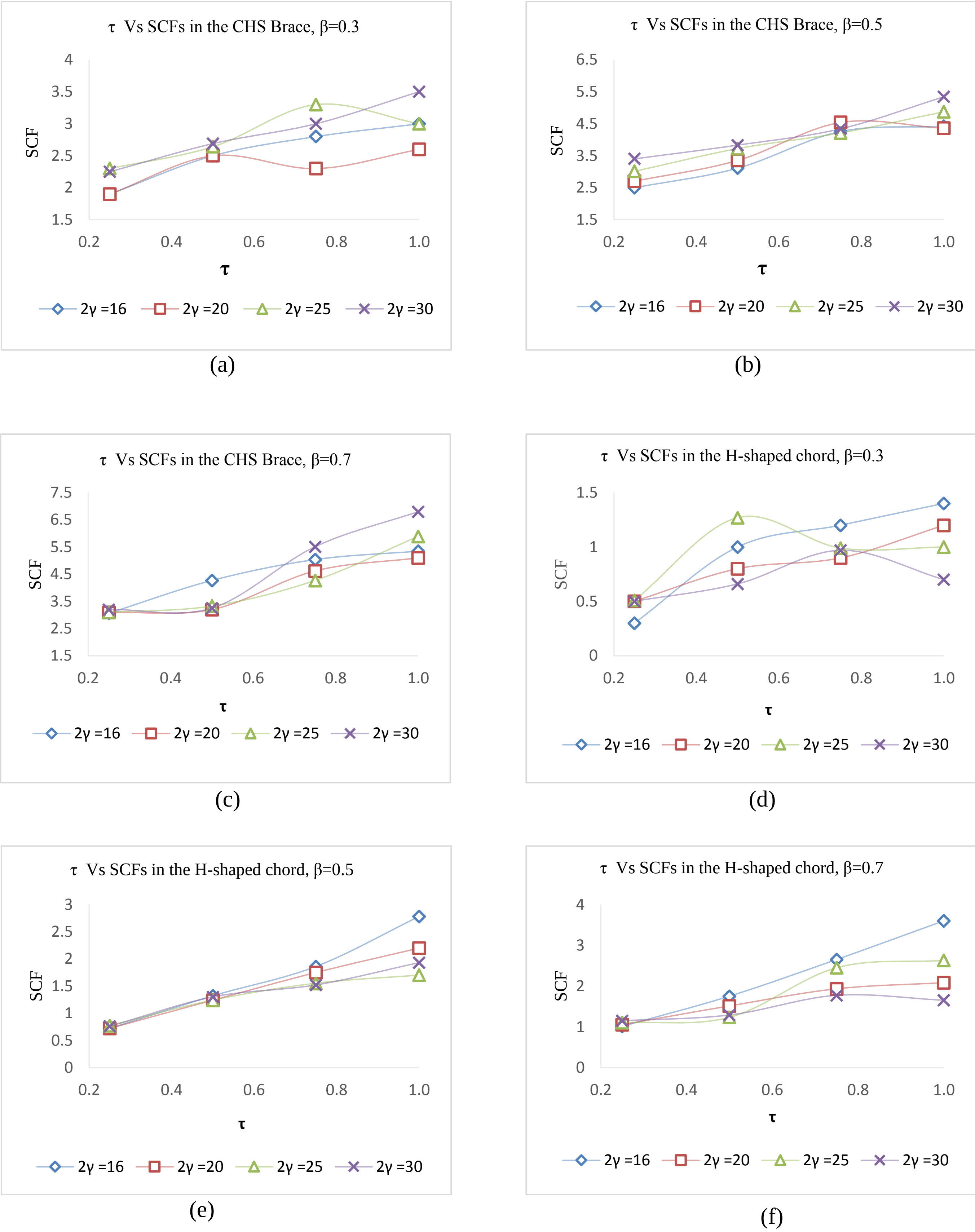
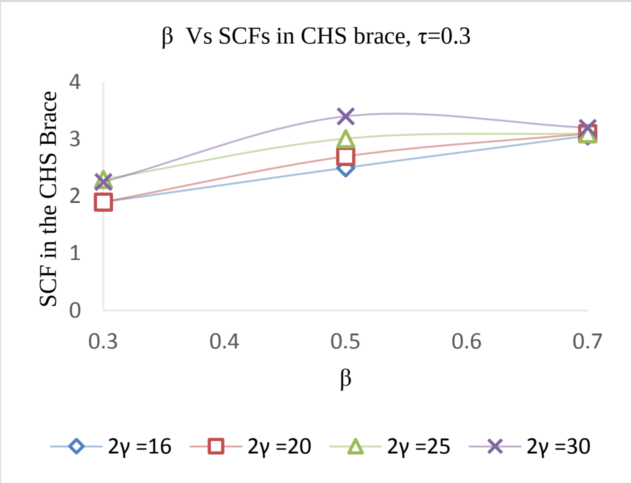
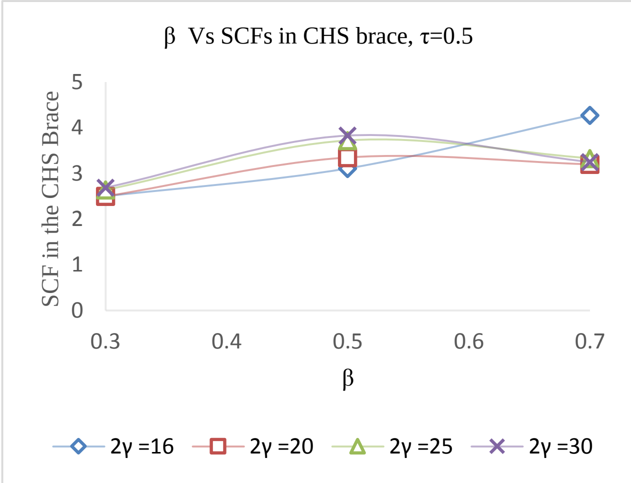


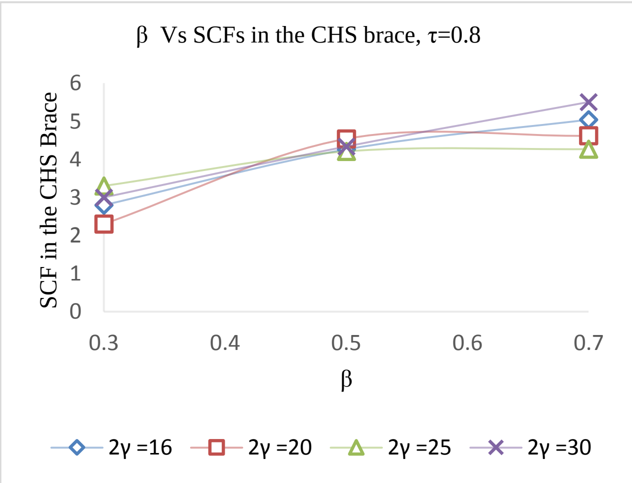
Figure 15. variation of SCF in CHS brace and H-shaped chord with τ


β Vs SCFs in CHS brace, τ=0.3
SCF in the CHS Brace
0
1
2
3
4
0.3
0.4
0.5
0.6
0.7
β
2γ =16
2γ =20
2γ =25
2γ =30

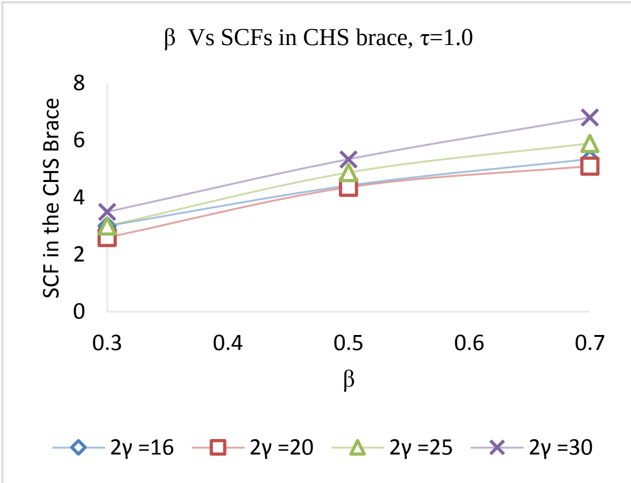
(a)


β Vs SCFs in CHS brace, τ=0.5
SCF in the CHS Brace
0
1
2
3
4
5
0.3
0.4
0.5
0.6
0.7
β
2γ =16
2γ =20
2γ =25
2γ =30

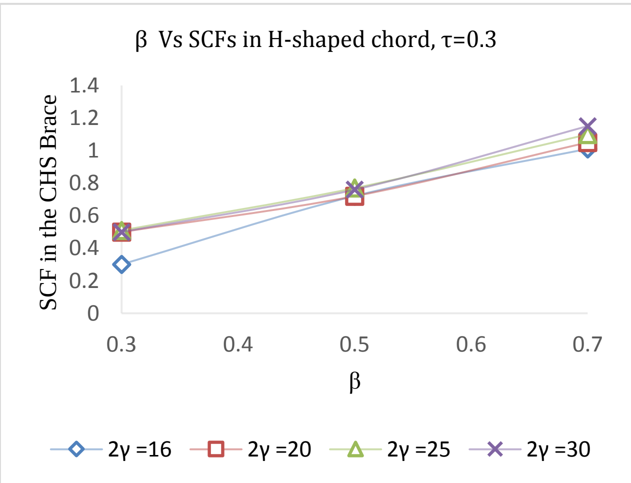
(b)


β Vs SCFs in the CHS brace, τ=0.8
SCF in the CHS Brace
0
1
2
3
4
5
6
0.3
0.4
0.5
0.6
0.7
β
2γ =16
2γ =20
2γ =25
2γ =30

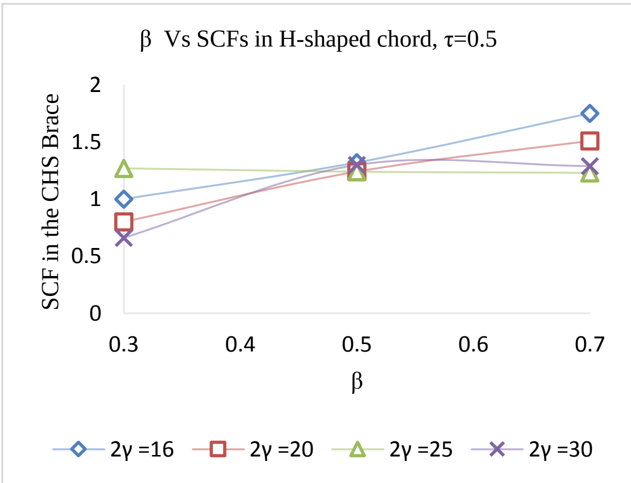
(c)


β Vs SCFs in CHS brace, τ=1.0
SCF in the CHS Brace
0
2
4
6
8
0.3
0.4
0.5
0.6
0.7
β
2γ =16
2γ =20
2γ =25
2γ =30

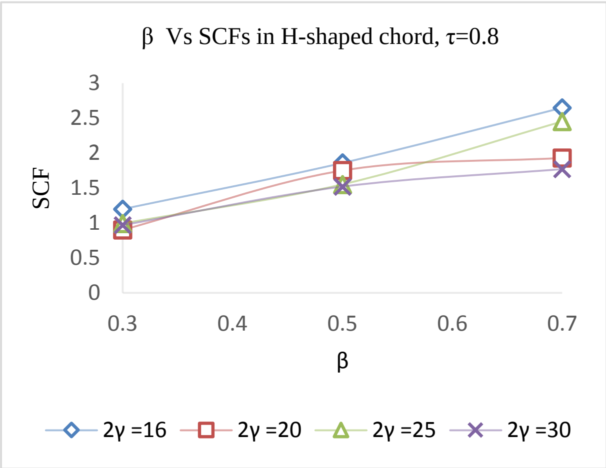
(d)

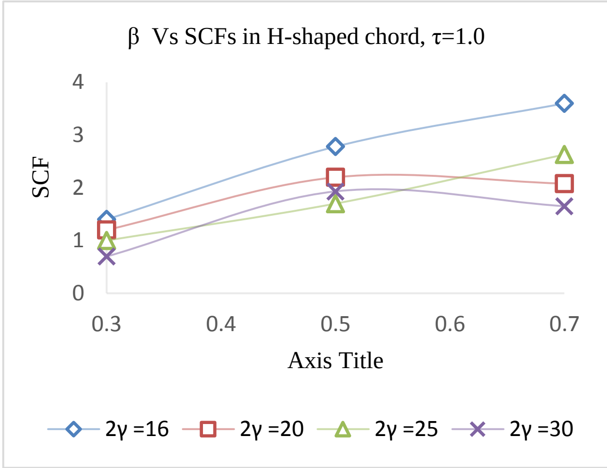

β Vs SCFs in H-shaped chord, τ=0.3
SCF in the CHS Brace
0
0.2
0.4
0.6
0.8
1
1.2
1.4
0.3
0.4
0.5
0.6
0.7
β
2γ =16
2γ =20
2γ =25
2γ =30

(e)


β Vs SCFs in H-shaped chord, τ=0.5
SCF in the CHS Brace
0
0.5
1
1.5
2
0.3
0.4
0.5
0.6
0.7
β
2γ =16
2γ =20
2γ =25
2γ =30

(f)



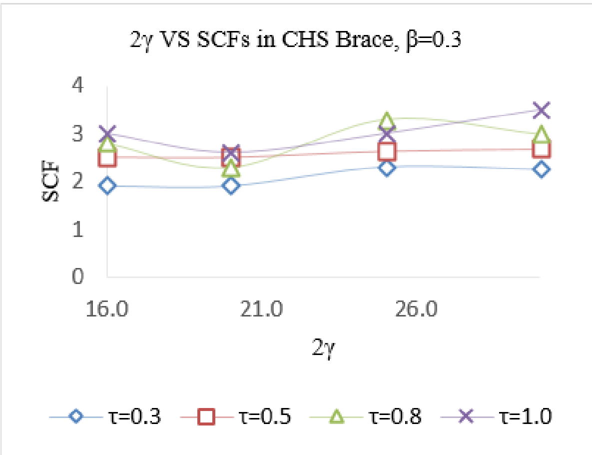


(g) (h)

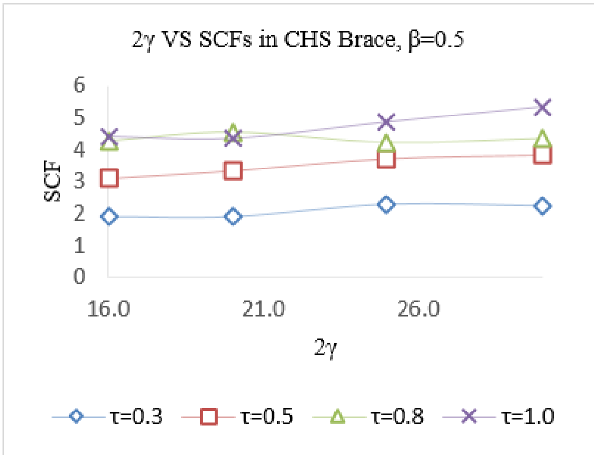
Figure. 16 variation of SCF in CHS brace and H-shaped chord with β

5.5. Effect of H-shaped Chord Flange Width to Thickness Ratio (2γ)

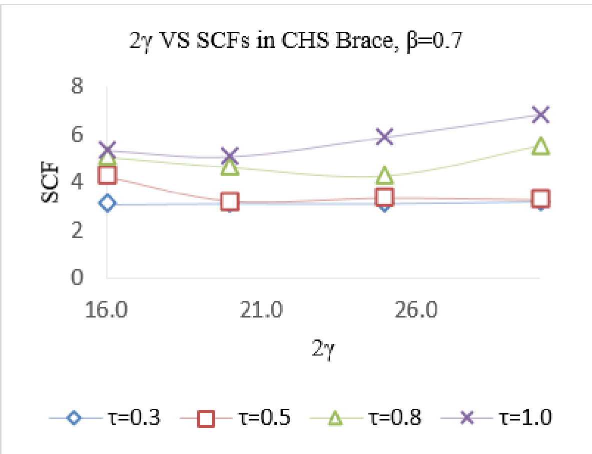
The range of the parameter 2γ is [16-30]. For all models, the chord width is 200 mm. so, increasing 2γ means that the thickness of the H-shaped flange increases accordingly. The parameter 2γ has the least effect on SCFs variations in the brace and the chord. Generally, as 2γ increases, SCFs in the brace remain unchanged or slightly increase. Figure 17 presents the variation of SCFs with 2γ for different values of β (0.3, 0.5 and 0.7) and τ(0.3, 0.5, 0.8 and 1.0). Referring to Figure 17, it can be concluded that changing the flange width of the chord compared to its thickness almost has no serious effect on the distribution of SCFs in the CHS brace or H-shaped chord.



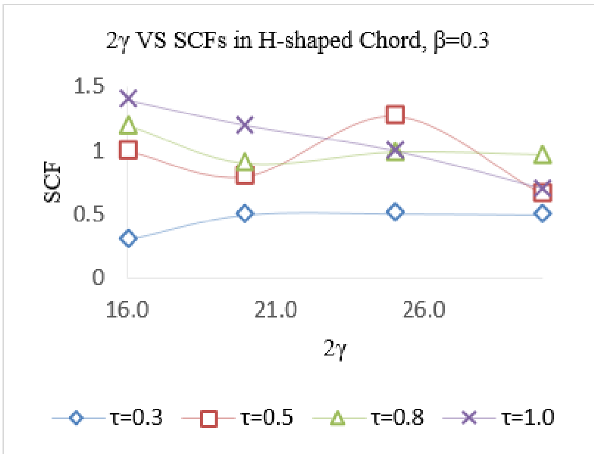
(a)



(b)



(c)



(d)

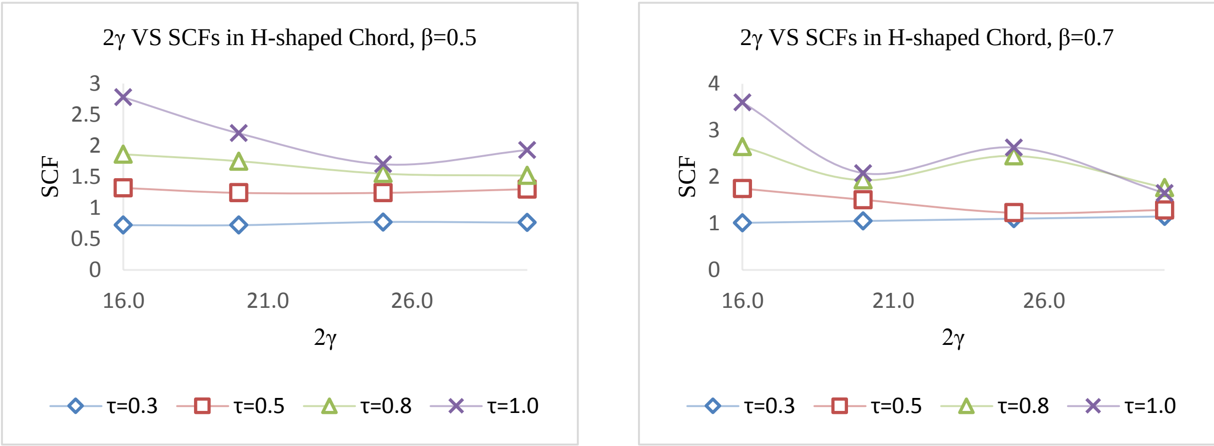


Figure 17. Variation of SCF in CHS brace and H-shaped chord with 2γ

6. Conclusion

This paper presented a comprehensive study on stress concentration factors in circular hollow section brace welded to H-shaped chord steel connection. The effect of non-dimensional geometric parameters has been carefully investigated by conducting finite element study using the commercial general-purpose finite element Abaqus software. The result of literature review presented in the introduction reveals that this type of welded connections has not been investigated by researchers for fatigue design under axial compression. Firstly, available experiments were used to verify the use of finite elements for prediction of stress concentration factors. Afterwards, an extensive parametric study has been performed to clarify the effect of CHS brace diameter to H-shaped chord flange width ratio (β), H-shaped chord flange width to thickness ratio (2γ) and CHS brace thickness to H-shaped chord flange thickness ratio (τ) on the distribution of SCFs in the CHS brace and the H-shaped chord. 48 finite element models have been investigated with parameters ranges; β=0.3-0.7, 2γ=16-30 and τ=0.3-1.0. It was found the SCFs in the CHS brace are generally larger than the corresponding ones in the H-shaped chord. Moreover, it was found that increasing the parameters β or τ would result in an increase in SCFs in the brace and the chord. On the other hand, increasing the parameter 2γ has generally no effect on the SCFs in the brace or the chord. Necessary graphs presenting the effect of each parameter on the variation of SCFs in the brace and the chord are presented.

7. Notations

CHS	Circular hollow section
FEA	finite element analysis
E	Elastic modulus
ν	Poisson's ratio
b_f	Flange width of H-shaped chord flange
b_w	Effective width of H-shaped chord web
t_f	Thickness of H-shaped chord flange
t_w	Thickness of H-shaped chord web
r	Corner radius of H-shaped chord
h	Over all height of H-shaped chord
h_1	External diameter of CHS brace
t_1	Thickness of CHS brace
Θ	Angel between CHS brace and H-shaped chord
β	CHS brace diameter to H-shaped chord flange width ratio
2γ	H-shaped chord flange width to thickness ratio
τ	CHS brace thickness to H-shaped chord flange thickness ratio

8. Conflicts of Interest

The authors declare no conflict of interest.

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