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Research on Hot Spot Stress Calculation Method of CHS-CFSHS Joints

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ABSTRACT

Fatigue behavior of welded joints is studied using hot spot stress method. In this case, the hot spot stress calculation method must be given. This paper dealt with hot spot stress of CHS-CFSHS T-joints made up of circular hollow section (CHS) braces and concrete-filled square hollow section (CFSHS) chords. Seven finite element models were established to calculate and analyze extrapolation region, extrapolation methods, strain concentration factors (SNCFs) and other related aspects of hot spot stress when braces were under axial tension. The paper examined the accuracy of the finite element calculation model and the reliability of the calculated results and clearly defined the calculation method of hot spot stress of CHS-CFSHS welded joints. Research showed that the finite element calculation method and model presented in the paper could accurately calculate SNCFs of CHS-CFSHS T-jonits. The extrapolation method to determine SNCFs had clear physical meanings and desirable results; the extrapolation region of pure SHS joints can be used as the extrapolation region of CHS-CFSHS joints for calculating SNCFs. SNCF numerical values obtained by quadratic extrapolation should be the result of finite element calculation of SNCFs of CHS-CFSHS joints.

KEYWORDS: CHS-CFSHS welded joints, Strain concentration factors (SNCFs), Hot spot stress calculation, Finite element analysis, Extrapolation methods.

INTRODUCTION

Concrete-filled steel tube (CFST) structure is a composite structure which belongs to the category of steel tube structures. The new structure embodies many advantages, such as high bearing capacity, good seismic and fire resistance performance, short construction period,… etc. It adapts to the needs of large-span, towering, overloaded and industrialized construction of modern engineering structures (Han and Yang, 2007; Han et al., 2014). At home and abroad, it has been popularized and applied in industrial plants, high-rise buildings, bridges and various structures. Compared with other types of joints, the welded CFST joints show more superiority in engineering practice. The appearance is simple and neat and there are no protruding node parts. The force transmission line is clear and the structure is simple. Moreover, maintenance is easy. With the wide application of CFST structure, static strength, stiffness, seismic performance and fatigue performance of CFST welded joints become an important research object in the field of tube structure. For bridges and offshore platforms which bear long-term alternating loads, fatigue performance of joints is one of the control factors of structural safety. For high-rise structures bearing long-term wind loads and some other structures, fatigue performance of joints is also an

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important indicator that can not be neglected.

Among the methods of fatigue strength analysis of steel tube joints, hot spot stress method has become the trend of fatigue calculation of welded tube joints and has made great achievements (DNV RP-C203, 2001; Zhou et al., 2001; IIW, 2008; AWS D1.1, 2008; Packer et al., 2007; Mashiri and Zhou, 2010; Mashiri et al., 2013; Wang et al., 2013; Kim et al., 2014; Qian et al., 2014; Tong et al., 2015; Tong et al., 2016). However, when hot spot stress method is used to calculate the fatigue performance of the joints, the calculation method of hot spot stress for different types of joints and the fatigue strength curve based on hot spot stress are the two most important research subjects. For different definitions of hot spot stress, the corresponding fatigue strength curves are different. So, hot spot stress is the stress index linked to fatigue strength curve. The different definitions used for hot spot stress make the comparison of different test results, numerical simulation results and design proposals meaningless. So, if fatigue behavior of welded joints is studied using hot spot stress method, the calculation method of hot spot stress must be given.

This paper dealt with hot spot stress of CHS-CFSHS T-joints made up of circular hollow section (CHS) braces and concrete-filled square hollow section (CFSHS) chords. T-joint was not only a common joint type in practical engineering, but also a basic joint type that made up more complex plane joints and space joints. According to the geometric parameters and materials of experimental joints in relevant literature (Tong et al., 2013), seven finite element models were established in this paper. In the paper, finite element software was used to calculate and analyze the extrapolation region, extrapolation method, SNCFs and other related aspects of hot spot stress of CHS-CFSHS T-jonits when braces were under axial tension. The paper also examined the accuracy of the finite element calculation model and the reliability of the calculated results and clearly defined the calculation method of hot spot stress of CHS-CFSHS welded joints.

Calculated Specimens

The main influencing parameters of steel tube joints were $\beta=d_1/b_0$, $2\gamma=b_0/t_0$ and $\tau=t_1/t_0$ in actual engineering. These parameters were generally in the following range: $0.35<\beta<1$, $12.5<2\gamma<30$, $0.25<\tau<1$. The paper obtained calculated specimens（CT1～CT7）by using the orthogonal design method to change each parameter 3 times within the ranges. Calculated area of the joints was away from the end of the pipe with a distance greater than 2.5 times of the length or diameter of the tube, in order to eliminate the influence of the end of tube on stress distribution in the joint area. The schematic diagram of CHS-CFSHS T-joint is shown in Figure 1. The plane view of calculated strain position in the specimen is shown in Figure 2. The size of calculated specimens and non-dimensional parameters are shown in Table 1. The calculated specimen data was the same as the corresponding experimental data in relevant literature (Tong et al., 2013).

Table 1. Calculated specimens (geometric parameters and material properties of experimental specimens)

Specimen no.	Steel grade	Concrete grade	SHS chord (mm)			CHS brace (mm)			Non-dimensional geometric parameters		
			b_0	t_0	L_0	d_1	t_1	L_1	$\beta= d_1/b_0$	$2\gamma= b_0/t_0$	$\tau= t_1/t_0$
CT1	Q345B	C50	250	12	1540	133	6	665	0.532	20.83	0.500
CT2			250	12	1540	133	4	665	0.532	20.83	0.333
CT3			250	12	1540	133	10	665	0.532	20.83	0.833
CT4			250	10	1540	133	5	665	0.532	25.00	0.500
CT5			250	8	1540	133	4	665	0.532	31.25	0.500
CT6			200	10	1360	133	5	665	0.665	20.00	0.500
CT7			300	12	1800	133	6	665	0.443	25.00	0.500

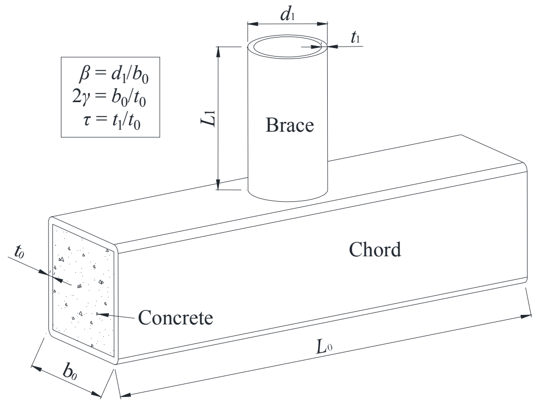


Figure (1): Schematic diagram of CHS-CFSHS T-joint

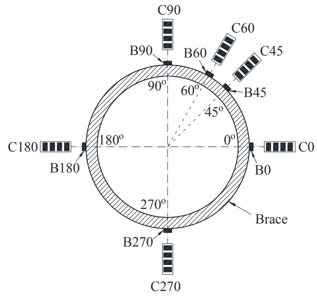


Figure (2): Plane view of calculated strain position

Finite Element (FE) Model

In this paper, ABAQUS was used for finite element analysis and calculation. The 1/2 finite element model was established by using the symmetry of joints (SIMULIA, 2013). The steel in this paper adopted the uncoordinated unit called C3D8I for calculation. The concrete adopted the linear reduced integral unit called C3D8R for calculation. The face-to-face discrete method was used between steel tube and for concrete to simulate the contact between steel tube and concrete. It adopted "hard" contact to simulate normal contact and used the Kulun friction model to simulate tangential bond and slip, of which the friction coefficient was taken as 0.35. The purpose of the paper was not to calculate the bearing capacity of CFST joints, but to obtain the stress concentration factor of the whole joint during the normal working process. Therefore, the tedious constitutive relation of concrete was not considered in this paper. The elastic modulus and Poisson's ratio of steel were taken as follows: $E = 2.05 \times 10^5$MPa，$\nu = 0.3$. The elastic modulus and Poisson's ratio of concrete were: $E = 3.45 \times 10^4$MPa, $v = 0.2$. In finite element modeling, the welding foot size took the average value of the measured points (Tong et al., 2013; Tong et al., 2013) and the weld was simplified as a triangle. In order to obtain a good balance between calculation accuracy and efficiency, taking joint CT1 as an example, different mesh accuracy values were compared and the final mesh is shown in Figure 3. The working condition of axial tension in the brace of the specimen is shown in Figure 4. According to the law of fatigue failure, the force acting on the joint was in the elastic state during the whole tensile condition.

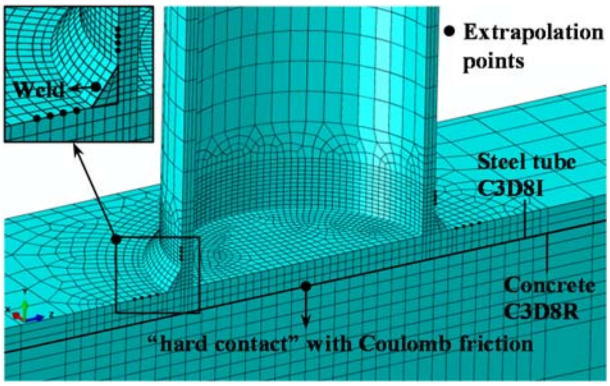


Figure (3): **FE mesh of a CHS-CFSHS T-joint (partial)**

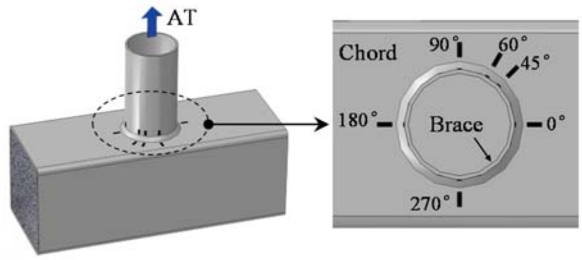
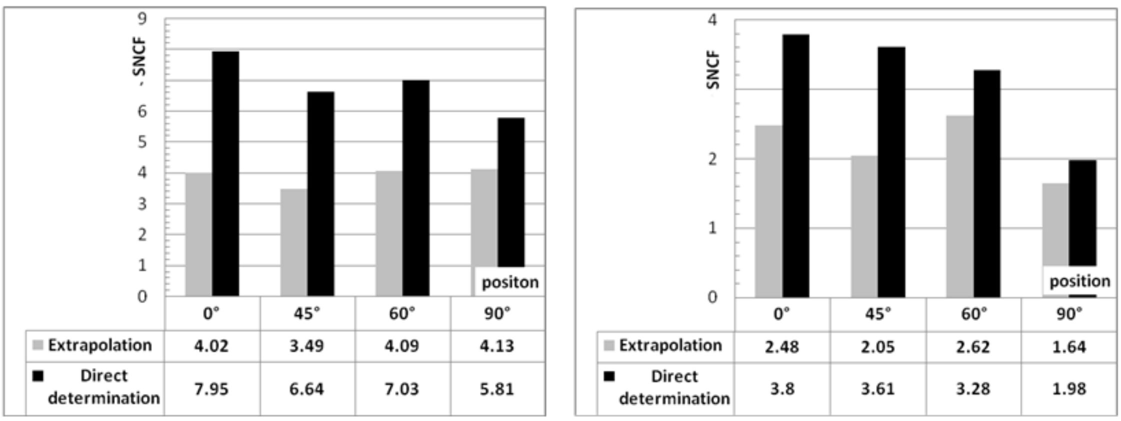


Figure (4): Working condition of axial tension in the brace

Comparison and Analysis of Two Methods to Determine SNCFs

Theoretically speaking, how to determine SNCFs has two methods: one is the direct determination method and the other is the extrapolation method. The so-called direct determination method is that the strain at the weld toe of the finite element model and perpendicular to the weld toe is divided by the corresponding nominal strain for SNCF determination. The so-called extrapolation method is that the hot spot strain obtained by extrapolation is divided by nominal strain values for SNCF determination. Although the direct determination method is convenient and easy to operate by eliminating the extrapolation process of the calculation, whether the method is reasonable or not is debatable.

In general, when using the extrapolation method for SNCF determination, the results of quadratic extrapolation are greater than the results of linear extrapolation. To illustrate that problem, under axial tension conditions of specimens (CT1~CT7), this paper compared the SNCF results of quadratic extrapolation with the SNCF results of direct determination, as shown in Table 2. For better understanding, the calculation results of specimens CT1 and CT2 were selected for comparison, as shown in Figure 5. As could be seen from Table 2 and Figure 5, the SNCF results of direct determination were larger than the SNCF results of quadratic extrapolation. The strain of direct determination method was equivalent to the strain at the welded joint, the influencing factors of which include the geometry of the structure, the abrupt change of section and the form of the weld (defect), while the strain of extrapolation method was focused on determining hot spot strain, mainly considering the influence of structure geometry. In the overall idea of calculating fatigue problems by hot spot stress method, the numerical value of hot spot stress must reflect to some extent the degree of stress concentration at the weld toe. In the actual project, the total impact of ever-changing, uncontrollable factors (weld shape, residual stress, defects,… etc.) must be quantified in the S-N curve through statistical methods. Welding defects were controlled by the corresponding weld quality. Therefore, the extrapolation method for SNCF determination was more in line with the requirement of the hot spot stress method to calculate the fatigue problem.



(a) SNCF on the chord of CT1 **(b) SNCF on the chord of CT2**

Figure (5): Comparison of two methods for SNCF determination

Table 2. Comparison of two methods for SNCF determination

Joints	Data	SNCF on the chord				
		0°	**45°**	**60°**	**90°**	**average**
CT1	Extrapolation	4.02	3.49	4.09	4.13	
	Direct determination	7.95	6.64	7.03	5.81	
	Ex /D	51%	53%	58%	71%	58%
CT2	Extrapolation	2.48	2.05	2.62	1.64	
	Direct determination	3.80	3.61	3.28	1.98	
	Ex /D	65%	57%	80%	83%	71%
CT3	Extrapolation	5.53	6.51	7.48	6.44	
	Direct determination	7.28	6.70	7.78	6.90	
	Ex /D	76%	97%	96%	93%	91%
CT4	Extrapolation	2.87	3.76	4.10	3.12	
	Direct determination	9.18	10.06	12.25	12.37	
	Ex /D	31%	37%	33%	25%	32%
CT5	Extrapolation	4.78	6.30	8.95	10.25	
	Direct determination	8.17	11.13	14.48	15.33	
	Ex /D	59%	57%	62%	67%	61%
CT6	Extrapolation	2.67	2.16	2.13	0.60	
	Direct determination	5.93	3.90	3.20	1.10	
	Ex /D	45%	55%	67%	55%	55%
CT7	Extrapolation	4.44	4.81	5.49	6.71	
	Direct determination	9.47	11.30	13.95	15.13	
	Ex /D	47%	43%	39%	44%	43%

Extrapolation Region and Extrapolation Methods

In the case of the same finite element model, different extrapolation regions and extrapolation methods can lead to different hot spot stress values. The SNCF results of different extrapolation methods can reflect different degrees of strain concentration. So, the scientific and reasonable extrapolation region and extrapolation methods are needed.

Table 3. Hot spot stress extrapolation region

Distance from the weld toe		Chord	Brace
Pure CHS joints	minimum	$0.4t_0$, not less than 4mm	$0.4t_1$, not less than 4mm
	maximum	$0.09r_0$ $0.4(r_0t_0r_1t_1)^{0.25}$	$0.65(r_1t_1)^{0.5}$
Pure SHS joints	minimum	$0.4t_0$, not less than 4mm	$0.4t_1$, not less than 4mm
	maximum	minimum+ t_0	minimum+ t_1

Extrapolation Region

In order to eliminate the influence of weld local defects and weld size on SNCF value, the starting point of extrapolation region should leave a certain distance from the weld toe. To incorporate the influence of the change of geometric stiffness in the joint area on the stress and reflect the stress gradient in the joint area, the ending point of the extrapolation area should be within a certain distance from the weld toe. All extrapolation points should lie in the region range (Tong et al., 2013). CIDECT (Zhou et al., 2001) provides different extrapolation regions for pure CHS joints and pure SHS joints, as shown in Table 3. In relevant literature (Tong et al., 2013), the gradient strain gauges of the experimental joints were arranged in the extrapolation region of pure SHS joints based on finite element analysis, taking rationality and ease of use into account.

Taking CT4 finite element calculation results as an example, analysis was conducted by properly changing the distance from extrapolation points to weld toe. If proper changes of extrapolation points in the extrapolation region only caused a small variation of SNCF value, the extrapolation region of pure SHS joints could be used as the extrapolation region of CHS-CFSHS joints. Analysis results of different distances from extrapolation points to weld toes are shown in Table 4. -2 represents the SNCF value obtained by finite element calculation when the distance from the extrapolation point to weld toe is 2 mm less than that of the experimental specimen. 0 represents the SNCF value obtained by finite element calculation when the distance from the extrapolation point to weld toe is the same as that of the specimen. +2 represents the SNCF value obtained by finite element calculation when the distance from the extrapolation point to weld toe is 2 mm more than that of the specimen. It could be seen from Table 4 that with proper changes in the extrapolation region of the finite element model, the difference between the SNCF values was not more than 10%. Therefore, the extrapolation region of pure SHS joints could be used as the extrapolation region of CHS-CFSHS joints.

Table 4. SNCF comparison of different distances from extrapolation point

Working condition and position		**SNCF**			**SNCF deviation**	
		0	**-2**	**+2**	**-2**	**+2**
Axial tension	Brace 0°	2.21	2.41	2.13	9.3%	-3.4%
	Brace 60°	5.37	5.69	4.97	6.0%	-7.5%
	Brace 90°	6.98	6.82	6.31	3.3%	-6.6%
	Chord 0°	2.87	3.12	2.62	8.6%	-8.7%
	Chord 60°	4.10	4.50	3.89	9.8%	-5.2%
	Chord 90°	3.12	3.42	2.91	9.5%	-6.7%

Table 5. SNCF values obtained by finite element (FE) method

Joints	Data	Extrapolation methods	SNCF on the brace					SNCF on the chord				
			0°	45°	60°	90°	Average	0°	45°	60°	90°	Average
CT1	FE	linear	3.54	3.75	4.91	**5.45**		3.51	3.33	3.92	**3.50**	
		quadratic	5.70	4.37	5.59	**6.15**		4.02	3.49	4.09	**4.13**	
		quadratic / linear	161%	116%	114%	113%	126%	114%	105%	104%	118%	110%
CT2	FE	linear	2.08	3.67	4.39	**5.15**		2.00	2.34	**2.32**	1.49	
		quadratic	2.53	4.26	5.01	**5.80**		2.48	2.05	**2.62**	1.64	
		quadratic / linear	122%	116%	114%	113%	116%	124%	88%	113%	111%	109%
CT3	FE	linear	1.03	3.31	4.39	**5.64**		5.38	6.46	**6.38**	5.19	
		quadratic	1.46	3.87	5.04	**6.40**		5.53	6.51	**7.48**	6.44	
		quadratic / linear	142%	117%	115%	113%	122%	103%	101%	117%	124%	111%
CT4	FE	linear	1.88	3.80	4.82	**6.13**		2.93	3.54	**3.77**	4.31	
		quadratic	2.21	4.29	5.37	**6.76**		2.87	3.76	**4.10**	3.12	
		quadratic / linear	118%	113%	111%	110%	113%	98%	106%	109%	72%	96%
CT5	FE	linear	2.11	4.81	6.54	**8.55**		4.04	5.90	8.04	**8.63**	
		quadratic	2.99	5.88	7.69	**9.79**		4.78	6.30	8.95	**10.25**	
		quadratic / linear	142%	122%	117%	114%	124%	118%	107%	111%	119%	114%
CT6	FE	linear	1.07	1.31	2.10	**2.72**		**2.43**	1.82	1.86	0.53	
		quadratic	1.13	1.33	2.06	**2.96**		**2.67**	2.16	2.13	0.60	
		quadratic / linear	106%	102%	98%	109%	104%	110%	118%	115%	113%	114%
CT7	FE	linear	2.01	3.83	4.82	**5.99**		3.55	4.48	5.08	**6.04**	
		quadratic	2.77	4.67	5.70	**6.94**		4.44	4.81	5.49	**6.71**	
		quadratic / linear	138%	122%	118%	116%	124%	125%	107%	108%	111%	113%

Extrapolation Methods

Table 5 and Table 6 give the finite element calculation results and the experimental results, respectively, when braces were under axial tension. Table 5 shows that the SNCF results on the brace obtained by quadratic extrapolation were significantly larger than those obtained by linear extrapolation, being 18% higher on average. Those on the chord were 10% higher on average. Table 6 shows that the SNCF results on the brace obtained by quadratic extrapolation were significantly larger than those obtained by linear extrapolation, being 24% higher on averae, while those on the chord were 4% higher on average. Because the SNCF numerical values calculated by quadratic extrapolation were generally larger than those calculated by linear extrapolation, in consideration of safety and unified extrapolation method, the SNCF numerical values obtained by quadratic extrapolation were adopted as the result of finite element calculation. From the results in Table 5 and Table 6, we can see that the ratio between the maximum SNCF value obtained by finite element calculations and the maximum SNCF value obtained by actual experiment ranged from 0.74 to 1.46, while the mean was 1.15, the variance was 0.05 and the dispersion degree was 0.043. In most cases, the finite element value was slightly higher than the experimental value.

Table 6. SNCF values obtained experimentally (exp.)

Joints	Data	Extrapolation methods	SNCF on the brace					SNCF on the chord				
			0 °	45°	60°	90°	Average	0°	45°	60°	90°	Average
CT1	Exp.	linear	2.33	3.25	4.55	**4.85**		2.97	2.77	2.88	**3.20**	
		quadratic	4.46	3.86	5.18	**5.67**		2.94	2.15	3.18	**3.23**	
		quadratic / linear	191%	119%	114%	117%	135%	99%	78%	110%	101%	97%
CT2	Exp.	linear	2.25	3.06	3.07	**4.48**		2.32	2.52	**2.53**	2.35	
		quadratic	3.77	4.09	3.00	**4.64**		2.07	2.69	**2.80**	2.67	
		quadratic / linear	168%	134%	98%	104%	126%	89%	107%	111%	114%	104%
CT3	Exp.	linear	0.52	1.66	2.15	**4.51**		4.55	4.90	**5.60**	4.08	
		quadratic	0.80	2.30	2.59	**4.54**		5.64	5.25	**6.08**	4.57	
		quadratic / linear	154%	139%	120%	101%	129%	124%	107%	109%	112%	113%
CT4	Exp.	linear	1.38	3.08	**4.47**	4.20		3.15	4.24	**4.91**	4.58	
		quadratic	1.63	4.03	**4.46**	3.16		3.28	4.47	**5.11**	3.22	
		quadratic / linear	118%	131%	100%	75%	106%	104%	105%	104%	70%	96%
CT5	Exp.	linear	1.46	⁄	4.48	**5.88**		4.06	5.76	7.12	**9.46**	
		quadratic	3.10	⁄	4.73	**7.99**		5.55	5.54	7.90	**8.32**	
		quadratic / linear	212%	⁄	106%	136%	139%	137%	96%	111%	88%	108%
CT6	Exp.	linear	0.77	3.15	2.01	**4.05**		**3.19**	1.85	1.62	0.25	
		quadratic	1.07	4.12	2.15	**3.99**		**3.11**	1.69	2.10	0.51	
		quadratic / linear	139%	131%	107%	99%	119%	97%	91%	130%	100%	105%
CT7	Exp.	linear	2.77	2.63	3.47	**4.41**		3.26	3.27	3.65	**4.75**	
		quadratic	4.04	2.36	3.69	**5.12**		3.04	3.46	3.58	**4.60**	
		quadratic / linear	146%	90%	106%	116%	115%	93%	106%	98%	97%	99%

In order to illustrate the problem, this paper made a comparison between the SNCF numerical values obtained by finite element calculation and the SNCF numerical values obtained by actual experiment, as shown in Fig. 6. From Fig. 6, Table 5 and Table 6, it can be seen that the calculated results of finite element analysis were in good agreement with the experimental results. The SNCF numerical values at each position obtained by finite element calculation, the maximum position and the trend were consistent with the experimental results. Based on the analysis, the finite element method and model in this paper could be used to calculate the SNCF values of CHS-CFSHS joints with good calculation accuracy and reliability.

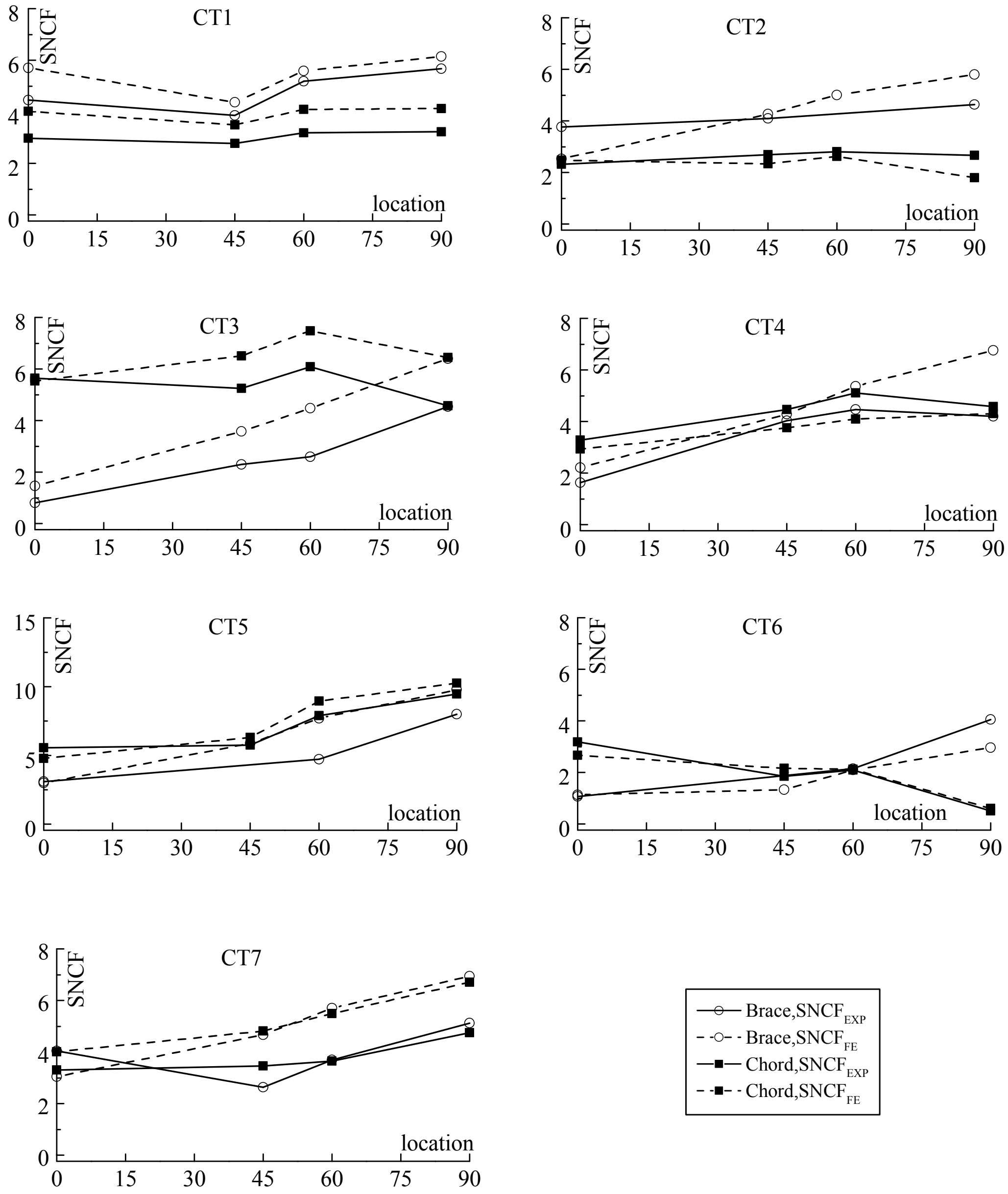


Figure (6): Comparison of SNCF FE analysis results and experimental results

CONCLUSIONS

In light of the results obtained from this study, the following conclusions can be drawn.

(1) The research showed that the finite element method and model used in this paper could be used to calculate SNCF values of CHS-CFSHS joints with good calculation accuracy and reliability.

(2) It was found that the extrapolation method for SNCF determination is desirable and has clear physical meanings.

(3) Results revealed that the extrapolation region of

pure SHS joints could be used as the extrapolation region of CHS-CFSHS joints for SNCF calculation.

(4) SNCF numerical values obtained by quadratic extrapolation should be taken as the result of finite element calculation in SNCF determination of CHS-CFSHS joints.

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