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Confining T-joints by adding two outer hollow ring flanges welded to additional hollow circular pipe

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ABSTRACT

Increasing the capacity of CHS T-joints is a challenge for the designers due to its closed nature which makes strengthening difficult as the traditional strengthening techniques focus on adding ring stiffeners inside the chord, these techniques require splitting the chord at each joint location into more than one part and this is not applicable for stiffening prefabricated and erected T-joints. This paper presents a proposed strengthening technique depends on confining the T-joint by two outer hollow ring flanges welded to additional hollow circular pipe. A parametric study is carried out to investigate the effect of the hollow ring flanges diameter, the added elements thickness, and the spacing between the hollow outer ring flanges on increasing the capacity of T-joints for different values of β (d_b/d_o : brace diameter-to-chord diameter ratio) when the brace is either subjected to tension or compression force. Finally, it is observed that the compressive T-joints gain up to 267% of its original capacity and the tensile T-joints gain up to 65% of its original capacity.

Key words: CHS, T-joint, Strengthening, stiffening, outer hollow ring.

1. INTRODUCTION

Welded circular hollow steel sections are commonly used in different kind of structures as they are required architecturally for their pleasing appearance, and they are also recommended structurally because of their reduced weight and surface area when compared to equivalent open steel profiles. The adequacy of the connection of CHS is an integral part of the CHS design, so it is important for engineer to be aware of different strengthening/stiffening techniques to choose the most suitable for the case. Strengthening and stiffening techniques can be classified into two types:

- I) Techniques in which stiffening elements are added inside the chord.
- II) Techniques in which stiffening elements are added on the outer surface of the chord.

Here is a brief literature review on some of different strengthening techniques for CHS T-joints that have been previously studied to increase the capacity of the joints:

For the first type of strengthening techniques, **Lee and Llewelyn-Parry (2004)** studied CHS T-joints strengthening by adding internal ring stiffeners to increase the strength of the joint and they also investigate the effect of β , γ (d_o/t_o : chord diameter-to-chord thickness), depth of the internal ring, thickness of the internal ring and the number of internal ring. **Shao, Lie and Chiew (2010)** stiffened the CHS T-joints subjected to axial compressive brace by thickening the chord near the brace-chord intersection and they clarified the effect of β , γ , and the thickness of reinforced chord to the thickness of unreinforced chord ratio. Welding an inner doubler plate to the internal surface of the chord at the brace-chord intersection is a technique that was studied by **Shubin, Yongbo and Hongyan (2013)**.

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For the second type of strengthening techniques, **Lesani, Bahaari, and Shokrieh (2013)** enhanced the capacity of the CHS T-joint subjected to axial brace compressive loading by adding fiber reinforced polymer. **Zhu, Zhao, Li, Huang, and Ban in (2014)** reinforced CHS T-joints by external stiffener and studied the effect of the length and the height of the stiffener. **Zhu, Han, Song, Ma, Wei and Li (2016)** carried out an experimental study to investigate the effect of adding external stiffening rings on improving the CHS T-joints axial compressive strength. Another technique using through bolts in the chord at the brace location was carried out by **Mohamed, Shaat, and Sayed-Ahmed (2013)** in this technique the gain in the joint strength reached 41%.

The disadvantage of strengthening technique type (I) is the impossibility of using it with erected CHS T-joints as it requires splitting the chord into more than one part to be able to add the stiffening elements inside the chord which is very difficult for execution. While the disadvantage of strengthening technique type (II) is either the CHS T-Joint doesn't gain much increasing in the capacity if small stiffeners are used, or the aesthetic appearance will be lost with using large stiffeners. Using outer collars of FRP is one of strengthening techniques type (II), but the low fire resistance of FRB is limiting the using of this method.

However, **Choo, Vegte, Zettlemoyer, and Liew (2005)** avoided the disadvantages mentioned above by reinforcing the T-joints by doubler plates or collar plates either under tensile or compression loading. The study provided the experimental results for four unreinforced specimens and also the experimental results of eight reinforced specimens. The study was extended to simulate the reinforced and unreinforced T-joints by numerical simulations which were well correlated with the experimental results. **Choo, Liang, and van der Vegte (2004)** continued on studying the effect of a collar plate by investigating the effect of collar plates on the capacity X-joints reinforced with a collar plate under different types of loading (axially compressive, in-plane bending and out of plane bending. Also **Nassiraei, Lotfollahi-Yaghin, and Ahmadi (2016)** extended the research on studying the effect of collar plate on reinforced tubular T/Y joints subjected to compressive brace by carrying out a parametric study to investigate the effect of plate size and joint geometry on the joint capacity, also a new equation based on nonlinear regression analysis was proposed to determine the ultimate compressive strength of reinforced T/Y joints.

In this study, proposed strengthening technique depends on confining the brace-chord intersection by using two outer hollow ring flanges -with diameter not much bigger than that of the chord so as not to lose the aesthetic appearance- in addition to welding a hollow circular pipe to these ring flanges (illustrated in Fig.1). Therefore, this new technique overcomes the disadvantage of strengthening types (I), (II) previously mentioned as it is applicable with prefabricated or erected CHS T-Joints with gaining up to 267% of its original compressive capacity and up to 65% of its original tensile capacity, without losing the circular aesthetic appearance of the circular hollow steel section. The behavior of this technique is studied in this paper numerically by performing 112 finite element models.

Fig.1. Confining T-joints by adding two outer hollow ring flanges welded to additional hollow circular pipe

From practical point of view, the fabrication of the proposed strengthening technique can be carried out by applying the following procedures which are clarified in (Fig.2):

- Step 1 → Fabricating the strengthening components in two equal parts. Each part consists of half circular pipe welded to two halves of ring flanges.
- Step 2 → Welding the additional hollow circular pipe (part 1) to the branch of the original unstiffened T-joint, and then welding the two outer hollow ring flanges (part 1) to the chord of the original unstiffened T-joint.
- Step 3 → Welding the additional hollow circular pipe (part 2) to the branch of the original unstiffened T-joint, and then welding the two outer hollow ring flanges (part 2) to the chord of the original unstiffened T-joint.
- Step 4 → Welding stiffening components of part (1) with that of part (2).

Fig.2. Fabrication procedure

2. FINITE ELEMENT MODELING

The first step taken in this study is to make sure that the finite element models are accurate and reliable for the parametric study and that is done by calibrating seven models with independent unreinforced specimens that have been tested experimentally, four of them were tested by Choo et al. (2005) and the other three were tested by Zhu et al. (2014). Table 1 shows Specimen ID (as per the reference), the CHS dimensions used in the tests.

Table 1. Specimens experimentally tested by Choo et al. (2005) and Zhu et al. (2014).

Reference	Specimen ID	Loading type	d_o (mm)	t_o (mm)	l_o (mm)	d_b (mm)	t_b (mm)	l_b (mm)
Choo et al. (2005)	EX-01	Compression	409.5	8.1	2840	221.9	6.8	1100
	EX-02	Tension	409.5	8.1	2840	221.9	6.8	1100
	EX-09	Compression	409.5	8.5	2840	114.7	5.9	1100
	EX-10	Tension	409.5	8.5	2840	114.7	5.9	1100
Zhu et al. (2014)	T1	Compression	298	5.6	1800	76.3	6.2	375
	T3	Compression	298.1	5.8	1800	147.2	6.4	745
	T5	Compression	297.9	6.1	1800	220.2	6.5	1126.5

a. ELEMENT TYPE AND MESHING

In this paper the numerical study is carried out by modeling 112 finite element models using software ANSYS 14. The steel elements in these models are simulated by using four node strain shell element “Shell 181” that is included in ANSYS elements library as the properties of this type of element is convenient for such simulation. Here is a brief description for the used shell element type: *SHELL181 “is suitable for analyzing thin to moderately-thick shell structures. It is a four-node element with six degrees of freedom at each node: translations in the x, y, and z directions, and rotations about the x, y, and z-axes. SHELL181 is well-suited for linear, large rotation, and/or large strain nonlinear applications”*. (Fig.3) shows the geometry, node locations, and the element coordinate system for this element.

As for the meshes size it was found that using size of 25 mm gives accurate realistic results when compared with that obtained from laboratory tests (this is shown below in section (2.d). Therefore, meshes of size 25 are used for all the elements in the numerical models in this paper.

Fig.3. Shell 181 used in FEM

b. MATERIAL MECHANICAL PROPERTIES

To represent the material mechanical properties in the finite element modeling, a bilinear isotropic hardening elastic perfectly plastic material is used. The material properties of the chord and brace of each model follows the same ones that used for the unreinforced specimens tested by Choo et al. (2005) and by Zhu et al. (2014). Table 2 shows mechanical properties used in the tests for each specimen; where E_o is the Young's modulus of the chords, E_b is the Young's modulus of the braces, $f_{y,o}$ is the yield stress for chords, and $f_{y,b}$ is the yield stress for braces. For the additional strengthening elements; the mechanical properties of the chord are followed.

Table 2. Mechanical properties of the specimens used for FEM calibration

Specimen ID	E_o (KN/mm ²)	E_b (KN/mm ²)	$f_{y,o}$ (N/mm ²)	$f_{y,b}$ (N/mm ²)
EX-01	200	200	285	300
EX-02	200	200	285	300
EX-09	200	200	276	312
EX-10	200	200	276	312
T1	227	224	345	470
T3	227	224	345	368
T5	227	183	345	352

c. WELD MODELING

In this study, the weld is considered to be complete joint penetration following the mechanical properties of the chord, while the weld thickness is following the thickness of connected steel elements.

d. LOADING AND BOUNDARY CONDITIONS

The brace load either compressive or tensile axial load is applied on thick ring plate which is placed on the brace end. The brace axial load is simulated by pressure or suction on the thick plate in order to ensure the uniformity of the load distribution.

For the calibration models of specimens ID (EX-01, EX-02, EX-09, and EX-10). The chord's two ends for a length of 150 mm was supported vertically (Y direction) and laterally (Z direction), but unrestrained longitudinally (X direction). For the brace end, it is supported horizontally in X, Z directions to follow the test arrangements mentioned by Choo *et al.* (2005). At the location of supports of the chord, thick vertical plates are added to match the test arrangement and to avoid the local failures at the supports. For the calibration models of specimens ID (T1, T3, T5) the chord's two ends were closed by a thick vertical plate. One end supported vertically, longitudinally and horizontally, while the other end supported vertically and horizontally. Note that these boundary conditions was only used for calibration the models of specimens ID (T1, T3, T5). The boundary conditions of specimens ID (EX-01, EX-02, EX-09, and EX-10) shown in Fig.4 are followed in all finite element models used for the parametric study.

Fig.4. FEM statical system used for the parametric study

e. FINITE ELEMENT MODELS VERIFICATION

Based on the element type, meshes size, material mechanical properties, loading and boundary conditions mentioned above in sections (2.a), (2.b) and (2.c) respectively the numerical results for seven models are obtained as shown in Table 3.

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Table 3. Experimental results compared to numerical results.

Specimen ID	Experimental Nominal strength P_{test} (KN)	Numerical Nominal strength P_{num} (KN)	P_{exp}/P_{num}	NOMINAL STRENGTH TYPE	error %
EX-01	-305.1	-305.4	1	peak load	0.1%
EX-02	+543.2	+567.3	0.96	ovalisation	4.2%
EX-09	-200.1	-176.2	1.14	peak load	13.6%
EX-10	+407.8	+413	0.99	ovalisation	1.30%
T1	-85	-87.8	0.97	peak load	3.2%
T3	-155	-163.3	0.95	peak load	5.1%
T5	-249.7	-276.2	0.90	peak load	9.6%
Average error %					5.3%
Notes: <ul style="list-style-type: none"> (+) sign denotes tensile load, (-) sign denotes compression load. Nominal strength is the minimum of peak load of the joint or the load opposite to ovalisation of $0.06d_o$ as mentioned by Choo et al. (2005). 					

173 The numerical results shown in Table 3 are well correlated with the experimental results with acceptable errors.
 174 Therefore, the finite element modeling as explained is trustable to be used in the parametric study. Another
 175 deformation limit criteria had been proposed by (Lu et al., 1994) which stated that the ultimate deformation limit
 176 occurs when the chord deformation reaches $0.03d_o$ indentation. Whether following the deformation limit criteria
 177 recommended by Choo et al. (2005) or (Lu et al., 1994), the nominal strength type mentioned in table 3 doesn't
 178 change. However, in determining the numerical nominal strength stated in table 3, Choo et al. (2005) deformation
 179 limit criteria was followed in order to be consistent with the experimental results obtained by Choo et al. (2005)
 180 which are already used in the finite element models verification in the current study.

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Fig.5. Experimental and numerical load-ovalisation curves

Fig. 5 represents the load-ovalisation curves for the calibrated finite element models against the experimental results provided by Choo et al. (2005) and Zhu et al. (2014). It is important to mention that for specimens (EX-01, EX-09, T1, T3 and T5) which are subjected to compression load, the load-ovalisation curves are plotted until the load reached the peak load as the behavior of the joints beyond the peak load isn't a part of the current study. While as for specimens (EX-02 and EX-04) which are subjected to tensile load, the ultimate load isn't the peak load, but it is the load corresponding to the deformation limit $0.06d_o$ as mentioned by Choo et al. (2005). This deformation limit is plotted as dashed line in Fig. 5 (b, d). Thus, it is concluded from Fig. 5 that there is good agreement between the behavior of the calibrated finite element models and that of the tests carried out by Choo et al. (2005) and Zhu et al. (2014).

3. PARAMETRIC STUDY

A parametric study is performed on CHS T-joints strengthened by the proposed technique (confining the brace-chord intersection by adding two outer hollow ring flanges welded to additional hollow circular pipe) to investigate the gain in the joint strength when compression or tension load is applied on the brace. This parametric study was done by applying the same finite element modeling aspects that were used in the calibration models (i.e. element type, meshing, material and loading). The parametric study has been carried out by performing 104 finite element models based on the calibration models. Half of the models are subjected to compressive brace (category I) and the other subjected tensile brace (category II), each category composed of four groups (A, B, C, D), and each group consists of fourteen models. In each group the chord and brace geometric/material parameters are fixed. In all groups the chord diameter-to-double of the chord thickness ratio ($2\gamma = d_o/t_o$) is almost constant; while the brace diameter-to-chord diameter ratio ($\beta = d_b/d_o$) varies from group to another. Tables 4 shows the brace-chord profiles, γ and β , used in each group for category (I), (II) respectively. The brace-chord profiles dimensions were chosen in order to follow the unreinforced specimens that have been tested experimentally by Choo et al. (2005) and Zhu et al. (2014). As these specimens have covered a wide range of the brace diameter-to-chord diameter ratio ($\beta = d_b/d_o$) with almost constant values of chord diameter-to-double the chord thickness ratio ($2\gamma = d_o/t_o$).

In each group:

- The radial flange diameter-to-chord diameter (d_s/d_o) has five values that varies from 1.1 to 1.5.
- The stiffening elements thickness-to-chord thickness ratio (t_s/t_o) has five values varies from 0.75 to 1.75.
- The additional pipe length-to-brace length ratio (l_s/d_b) five values that vary from 1.1 to 3.

TABLE 4. Chord-brace profiles' dimensions used in the numerical study.

CATEGORY	GROUP	CHORD DIMENSIONS		BRANCH DIMENSION		γ	β
		d_o	t_o	d_b	t_b		
I	I-A	409.5	8.1	221.9	6.8	25.28	0.54
	I-B	409.5	8.5	114.7	5.9	24.09	0.28
	I-C	298.1	5.8	147.2	6.4	25.70	0.49
	I-D	297.9	6.1	220.2	6.5	24.42	0.74
II	II-A	409.5	8.1	221.9	6.8	25.28	0.54
	II-B	409.5	8.5	114.7	5.9	24.09	0.28
	II-C	298.1	5.8	147.2	6.4	25.70	0.49
	II-D	297.9	6.1	220.2	6.5	24.42	0.74

All dimensions are in mm.

4. FINITE ELEMENT MODELS RESULTS

Six of the above mentioned calibration models were used to be part of parametric study models, four of these six models -with ID (EX-01, EX-02, EX-09, and EX-10)- were used to be the unreinforced models that will be

strengthened by the new technique in the numerical study, so the results of models I-A-01, I-B-01, II-A-01, II-B-01 in tables (5, 6) are the same as the results of relevant calibration models -mentioned in table 2-. While for the calibration models -with ID (T3, T5) - some modifications were applied on the calibration models to unify the parameters to be similar to that of other specimens-with ID (EX-01, EX-02, EX-09, and EX-10)-. This is the cause of the slight difference between the results of models I-C-01, I-D-01 and the results of calibration models of specimen T3, T5.*

**[These modifications are applied on the chord span, the brace length, and the boundary conditions so as to be similar to that of specimens with ID (EX-01, EX-02, EX-09, and EX-10).]*

In each group the model with ID 01, the T-joint is unreinforced. For models with ID (02 to 06), the strengthened T-joint is studied to investigate the effect of (d_s/d_o) . For models with ID (07 to 10), the strengthened T-joint is studied with different values of (t_s/t_o) . The effect of (l_s/d_b) is studied in models with ID (11 to 14).

Tables 5, 6 shows the parameters values, the non-dimensional parameters values, the joint capacity, and the gain percentage in each model for category (I), (II) respectively. The results of finite elements models for category (I), (II) are also summarized in Fig.6, Fig.7 respectively. The gain in joint capacity is calculated as shown in equation Eq.1.

$$\text{Gain \%} = \frac{\text{strength of stiffened joint} - \text{strenght of unreinforced joint}}{\text{strenght of unreinforced joint}} \times 100 \quad \text{Eq. 1}$$

Fig.6. Summary for the numerical results of category (I)

Fig.7. Summary for the numerical results of category (II)

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Table 5. The FEM results after using the new stiffening technique with category I.

GROUP	MODEL ID	ADDED PIPE DIMENSIONS (mm)			NON-DIMENSIONAL PARAMETERS			JOINT CAPACITY (KN)	GAIN %
		ds	ts	ls	ds/do	ts/to	ls/db		
I-A	I-A-01	0	0	0	0.00	0.00	0.00	305.4	0.0%
	I-A-02	450.45	8.1	244	1.10	1.00	1.10	582	90.6%
	I-A-03	491.4			1.20			687	125.0%
	I-A-04	532.35			1.30			781	155.7%
	I-A-05	573.3			1.40			840	175.0%
	I-A-06	614.25			1.50			868	184.2%
	I-A-07	450.45	6.075	1.10	0.75	1.00	511	67.3%	
	I-A-08		10.125		1.25		644	110.9%	
	I-A-09		12.15		1.50		694	127.2%	
	I-A-10		14.175		1.75		739	142.0%	
	I-A-11		8.1		332.85		1.00	1.50	585
	I-A-12	443.8		2.00	589	92.9%			
	I-A-13	554.75		2.50	602	97.1%			
	I-A-14	665.7		3.00	593	94.2%			
I-B	I-B-01	0	0	0	0.00	0.00	0.00	176.2	0.0%
	I-B-02	450.45	8.5	126	1.10	1.00	1.10	399.5	126.7%
	I-B-03	491.4			1.20			504	186.0%
	I-B-04	532.35			1.30			595.5	238.0%
	I-B-05	573.3			1.40			625	254.7%
	I-B-06	614.25			1.50			625	254.7%
	I-B-07	450.45	6.375	1.10	0.75	1.00	346	96.4%	
	I-B-08		10.625		1.25		445.5	152.8%	
	I-B-09		12.75		1.50		486	175.8%	
	I-B-10		14.875		1.75		520	195.1%	
	I-B-11		8.5		172.05		1.00	1.50	400
	I-B-12	229.4		2.00	382	116.8%			
	I-B-13	286.75		2.50	372.5	111.4%			
	I-B-14	344.1		3.00	368	108.9%			
I-C	I-C-01	0	0	0	0.00	0.00	0.00	176	0.0%
	I-C-02	327.9	5.8	161.92	1.10	1.00	1.10	347	97.2%
	I-C-03	357.7			1.20			400.2	127.4%
	I-C-04	387.5			1.30			441.8	151.0%
	I-C-05	417.3			1.40			448.5	154.8%
	I-C-06	447.1			1.50			449	155.1%
	I-C-07	327.9	4.35	1.10	0.75	1.00	304.8	73.2%	
	I-C-08		7.25		1.25		385	118.8%	
	I-C-09		8.7		1.50		414	135.2%	
	I-C-10		10.15		1.75		431	144.9%	
	I-C-11		5.8		220.8		1.00	1.50	343
	I-C-12	294.4		2.00	343	94.9%			
	I-C-13	368		2.50	351	99.4%			
	I-C-14	441.6		3.00	351	99.4%			
I-D	I-D-01	0	0	0	0.00	0.00	0.00	299.9	0.0%
	I-D-02	327.7	6.1	242.22	1.10	1.00	1.10	468.5	56.2%
	I-D-03	357.5			1.20			480	60.1%
	I-D-04	387.3			1.30			486	62.1%
	I-D-05	417			1.40			486	62.1%
	I-D-06	447			1.50			486	62.1%
	I-D-07	327.7	4.575	1.10	0.75	1.00	440	46.7%	
	I-D-08		7.625		1.25		483	61.1%	
	I-D-09		9.15		1.50		486	62.1%	
	I-D-10		10.675		1.75		486	62.1%	
	I-D-11		6.1		330.3		1.00	1.50	482
	I-D-12	440.4		2.00	502	67.4%			
	I-D-13	550.5		2.50	510	70.1%			
	I-D-14	660.6		3.00	510	70.1%			

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Table 6. The FEM results after using the new stiffening technique with category II.

GROUP	MODEL ID	ADDED PIPE DIMENSIONS (mm)			NON-DIMENSIONAL PARAMETERS			JOINT CAPACITY (KN)	GAIN %
		ds	ts	ls	ds/do	ts/to	ls/db		
II-A	II-A-01	0	0	0	0.00	0.00	0.00	567	0.0%
	II-A-02	450.45	8.1	244	1.10	1.00	1.10	807.7	42.5%
	II-A-03	491.4			1.20			826.6	45.8%
	II-A-04	532.35			1.30			838.8	47.9%
	II-A-05	573.3			1.40			874	54.1%
	II-A-06	614.25			1.50			874	54.1%
	II-A-07	450.45	6.075	1.10	0.75	1.00	774.5	36.6%	
	II-A-08		10.125		1.25		858	51.3%	
	II-A-09		12.15		1.50		889	56.8%	
	II-A-10		14.175		1.75		889	56.8%	
	II-A-11		8.1		332.85		1.00	1.50	826.8
	II-A-12	443.8		2.00	857.9	51.3%			
	II-A-13	554.75		2.50	913	61.0%			
	II-A-14	665.7		3.00	936	65.1%			
II-B	II-B-01	0	0	0	0.00	0.00	0.00	413	0.0%
	II-B-02	450.45	8.5	126	1.10	1.00	1.10	600.6	45.4%
	II-B-03	491.4			1.20			617.6	49.5%
	II-B-04	532.35			1.30			618.7	49.8%
	II-B-05	573.3			1.40			618.7	49.8%
	II-B-06	614.25			1.50			618.7	49.8%
	II-B-07	450.45	6.375	1.10	0.75	1.00	560.5	35.7%	
	II-B-08		10.625		1.25		614	48.7%	
	II-B-09		12.75		1.50		614	48.7%	
	II-B-10		14.875		1.75		615	48.9%	
	II-B-11		8.5		172.05		1.00	1.50	614
	II-B-12	229.4		2.00	614	48.7%			
	II-B-13	286.75		2.50	614	48.7%			
	II-B-14	344.1		3.00	614	48.7%			
II-C	II-C-01	0	0	0	0.00	0.00	0.00	322	0.0%
	II-C-02	327.9	5.8	161.92	1.10	1.00	1.10	453	40.7%
	II-C-03	357.7			1.20			454.8	41.2%
	II-C-04	387.5			1.30			454.8	41.2%
	II-C-05	417.3			1.40			454.8	41.2%
	II-C-06	447.1			1.50			454.8	41.2%
	II-C-07	327.9	4.35	1.10	0.75	1.00	450	39.8%	
	II-C-08		7.25		1.25		459	42.5%	
	II-C-09		8.7		1.50		459	42.5%	
	II-C-10		10.15		1.75		459	42.5%	
	II-C-11		5.8		220.8		1.00	1.50	470.8
	II-C-12	294.4		2.00	486	50.9%			
	II-C-13	368		2.50	502	55.9%			
	II-C-14	441.6		3.00	520	61.5%			
II-D	II-D-01	0	0	0	0.00	0.00	0.00	470	0.0%
	II-D-02	327.7	6.1	242.22	1.10	1.00	1.10	497	5.7%
	II-D-03	357.5			1.20			495	5.3%
	II-D-04	387.3			1.30			496	5.5%
	II-D-05	417			1.40			494	5.1%
	II-D-06	446.8			1.50			489	4.0%
	II-D-07	327.7	4.575	1.10	0.75	1.00	496	5.5%	
	II-D-08		7.625		1.25		496	5.5%	
	II-D-09		9.15		1.50		496	5.5%	
	II-D-10		10.675		1.75		495	5.3%	
	II-D-11		6.1		330.3		1.00	1.50	514
	II-D-12	440.4		2.00	543	15.5%			
	II-D-13	550.5		2.50	570	21.3%			
	II-D-14	660.6		3.00	601	27.9%			

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251 **5. FAILURE MODES AND DEFORMED SHAPES**

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253 This part of the accompanied paper focuses on the joint behavior before and after strengthening by the proposed
254 technique. For each group, the deformed shape and the corresponding stress distribution across the chord/brace at
255 the brace chord intersection for unstiffened joints is compared to that of the stiffened joints to investigate the
256 performance of the new strengthening technique.

257 For groups (I-A, I-B, I-C, I-D and II-A) the joint behavior is compared between the unstiffened models (ID-01) and
258 the models with ID-02 which have smallest radial flange diameter ($d_s/d_o=1.1$), stiffening elements thickness equals
259 to the chord thickness ($t_s/t_o=1$) and smallest additional pipe length ($l_s/d_b=1.1$) in order to investigate the effect of the
260 parameters on strengthened joint. Also to investigate the effect of radial flange diameter parameter (d_s) individually,
261 the behavior of models with ID-06 which have the largest radial flange diameter ($d_s/d_o=1.5$) is compared with the
262 models with ID-02. To study the effect stiffening elements thickness (t_s) individually, the behavior of models with
263 ID-10 which have the largest stiffening elements thickness ($t_s/t_o=1.75$) is compared with the models with ID-02.
264 Similarly to investigate the effect of additional pipe length (l_s) separately, the behavior of models with ID-14 which
265 have the largest radial flange diameter ($d_s/d_o=1.5$) is compared with the models with ID-02.

266 While as for groups (II-B, II-C and II-D), the joint behavior is compared between the unstiffened models (ID-01)
267 and the models with ID-02 which have smallest radial flange diameter ($d_s/d_o=1.1$), stiffening elements thickness
268 equals to the chord thickness ($t_s/t_o=1$) and smallest additional pipe length ($l_s/d_b=1.1$). The behavior of this model
269 (ID-02) is similar to the rest of the models that is why the behavior of the other models (ID 06, 10 and 14) are not
270 shown in figures (18, 20 and 22).

271 **a. THE FAILURE MODE AND DEFORMED SHAPE FOR GROUP I-A**

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273 Fig. 8 The behavior of group I-A

Fig. 9 Load-ovalisation curves for FEM (I-A-01, I-A-02, I-A-06, I-A-10 and I-A-14)

For FEM I-A-01, Fig.8. (a) Shows that there is a good correlation between the deformed shape obtained from the FEM and from that of the tests which were carried out by (Choo et. al), also the figure clarifies that yield hinges occur in the chord upper half at the brace-chord intersection while the chord lower half hasn't been yielded yet.

While in FEM I-A-02, in addition to the yielded hinges that occurred in the chord upper half as mentioned above, yield hinges in the chord lower half also occurred which indicates that the chord upper half became stiffer against the local failure that was governing the unstiffened model (I-A-01). At the brace-chord intersection the brace wall is subjected to inelastic bending (clarified in Fig.8. (b)). Fig.9 clarifies that the joint with ID I-A-02 is more ductile than that of the unstiffened joint (I-A-01), and that happened due to yield hinges in the chord lower half.

Fig.8. (c) shows that the chord cross section at the brace- chord intersection (stiffened part) and just after the intersection in FEM I-A-06 became fully yielded which indicates that the chord reached its full bending capacity and eliminated the effect of the chord local failure that was governing the unstiffened model (I-A-01). The ovalisation decreased and chord deformed shape is almost circular. It is clear from the curves in Fig.9 that increasing the radial flange diameter increases the joint capacity and decreases the ductility than that of the joint with ID-A-02.

While Fig.8 (d) shows that the joint behavior is similar to that of model (ID-02) as shown in Fig.8 (b), the difference between them is that the stresses at chord/brace intersection is relaxed and yielded stresses plateau is extended to a wider zone when compared with that of model (ID-02). Curves in Fig.9 show clearly that increasing the stiffening elements thickness has a great effect on increasing the joint capacity, also it increased the joint ductility due to extending the limit of plastic zone.

In FEM I-A-14, Yield hinges that occurred in the chord lower half in model (I-A-02) disappeared (as shown in Fig.8 (e)) which indicates decreasing the confinement effect due to increasing the distance between the radial stiffeners, it is shown in Fig.9, that increasing the additional pipe length doesn't have significant effect on the joint capacity, as it is clear from the curve that the behavior of joint I-A-14 is too close to that of joint I-A-02 but with less ductility.

b. THE FAILURE MODE AND DEFORMED SHAPE FOR GROUP I-B

Fig. 10 The behavior of group I-B

Fig. 11 Load-ovalisation curves for FEM (I-B-01, I-B-02, I-B-06, I-B-10 and I-B-14)

As for FEM I-B-01, it is clear that there is a good correlation between the deformed shape obtained from the FEM and from that of the tests which were carried out by (Choo et. al) as shown in Fig.10 (a) also yield hinges occur in the chord upper half at the brace-chord intersection.

Fig. 10 (b) shows that in FEM I-B-02 at the brace-chord intersection the brace wall is subjected to inelastic bending due to increasing the chord stiffness comparing to that of the brace at the chord-brace intersection. Fig.11 clarifies that the joint with ID I-B-02 is more ductile than that of the unstiffened joint (I-B-01), also the joint capacity increased.

While in FEM I-B-06, the brace section is governing the joint capacity as it is fully yielded, also the chord deformed shape is almost circular as shown in Fig. 10 (c). As a result of that, the load-ovalisation curve of FEM I-B-06 shows that the ovalisation value is very small, also it shows that the failure is almost brittle as the brace compressive failure was the governing mode.

It is clear from Fig. 10 (d). that the inelastic bending of the brace wall at the brace-chord intersection in FEM I-B-10 is more than that in model I-B-02 due to increasing the stiffness of the chord compared to that in FEM I-B-02, but the joint capacity isn't governed by the brace capacity only. And that is clear from the curves in Fig.11 that the behavior of FEM I-B-10 is close to that of FEM I-B-02, also it shows that increasing the stiffening elements thickness has a great effect on increasing the joint capacity, and on increasing the joint ductility due to extending the limit of plastic zone.

In FEM I-B-14 (clarified in Fig. 10 (e)), the yielded zone that occurred in the brace wall at the brace-chord intersection due to the inelastic bending is less than that in FEM I-B-02 which indicates decreasing the confinement effect due to increasing the distance between the radial stiffeners. The curve of FEM I-B-14 in Fig.11, indicates that increasing the additional pipe length doesn't have significant effect on the joint capacity.

c. THE DEFORMED SHAPE AND FAILURE MODE FOR GROUP I-C

Fig. 12 The behavior of group I-C

Fig. 13 Load-ovalisation curves for FEM (I-C-01, I-C-02, I-C-06, I-C-10 and I-C-14)

In this group (d_b/d_o : brace diameter-to-chord diameter ratio= 0.49) which is close to that of group I-A where (d_b/d_o = 0.54), thus the behavior of these two groups are similar.

In FEM I-C-01, Yield hinges occur in the chord upper half at the brace-chord intersection (as shown in Fig.12 (a)).

Fig.12 (b) shows that yield hinges in the chord lower half occurred in FEM I-C-02 which indicates that the chord upper half became stiffer against the local failure that was governing model (I-C-01). Thus, the FEM I-C-02 becomes more ductile than FEM I-C-01 and that is seen clearly on the curves in in Fig.13

While in FEM I-C-06, The chord cross section at the brace- chord intersection (stiffened part) and just after the intersection the chord is fully yielded which indicates that the chord reached its full bending capacity and eliminated the effect of the chord local failure that was governing model (I-C-01), also the ovalisation decreased and chord deformed shape is almost circular and that was clarified in Fig.12 (c). Also Fig.13 (I-C-06) shows that increasing the radial flange diameter has clear effect on decreasing the joint ovalisation and ductility.

As for FEM I-C-10, the chord yielded zone increased and the chord cross section at the brace- chord intersection (stiffened part) and just after the intersection became fully yielded which indicates that the chord reached its full bending capacity and eliminated the effect of the chord local failure. At the brace-chord intersection the brace wall is subjected to inelastic bending due to increasing the chord stiffness comparing to that of the brace at the chord-brace intersection as shown in Fig.12 (d). The curves in Fig.13 (I-C-10) show clearly that increasing the stiffening elements thickness has a great effect on increasing the joint capacity, also it increases the joint ductility and extends the limit of plastic zone until the chord cross section was fully yielded which was the governing failure mechanism.

In FEM I-C-14, the Yield hinges zone that occurred in the chord lower half (as per Fig.12 (e)) is less than that occurred in FEM I-C-02 which indicates decreasing the confinement effect due to increasing the distance between the radial stiffeners. It is shown in Fig.13 that increasing the additional pipe length doesn't have significant effect on the joint capacity, as it is clear from the curve that the behavior of joint I-C-14 is too close to that of joint I-C-02, but with less ductility.

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d. THE DEFORMED SHAPE AND FAILURE MODE FOR GROUP I-D

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Fig. 14 The behavior of group I-D

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Fig. 15 Load-ovalisation curves for FEM (I-D-01, I-D-02, I-D-06, I-D-10 and I-D-14)

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In FEM I-D-01, (d_b/d_o : brace diameter-to-chord diameter ratio= 0.74 which is greater than the ratios of groups I-A and I-C), yield hinges occur in the upper and lower halves of the chord at the brace-chord intersection (as shown in Fig.14. (a)) which indicates that the chord local failure doesn't have a significant effect on the joint capacity as (I-A-01, I-B-01, and I-C-01).

As for FEM (I-D-02), the chord cross section at the brace- chord intersection (stiffened part) and just after the intersection is fully yielded (clarified in Fig.14 (b)) which indicates that the chord reached its full bending capacity and eliminated the effect of the chord local failure that was governing model (I-D-01). Fig.15 shows that FEM I-D-02 isn't more ductile than the unstiffened joint I-D-01 unlike the behavior in groups I-A, I-B and I-C. This is because the joint capacity in FEM I-D-02 was governed by the chord bending capacity and not by the chord local failure as in groups I-A, I-B and I-C.

While in FEM I-D-06 and I-D-10, the joint capacity is almost governed by the chord bending capacity, the ovalisation decreased significantly and chord deformed shape is almost circular as shown in Fig.14 (c, d). Which is clarified in Fig.15 as it shows that the ovalisation value is small at the peak load for FEM I-D-06 and I-D-10

Fig.14 (e) shows the chord yielded zone hinges that occurred in the chord upper half and lower half in model (I-D-14) decreased and the ovalisation is occurred which indicates decreasing the confinement effect due to increasing the distance between the radial stiffeners. In Fig.15, it is seen that FEM I-D-14 is stiffer than FEM I-D-02, because increasing the additional pipe length increases the chord bending capacity at the section that yielded in FEM I-D-02. In other words, the increasing of the length of the additional pipe is acting as a strengthening for the yielded parts of FEM I-D-02 which enhanced the capacity and the ductility as well.

e. THE DEFORMED SHAPE AND FAILURE MODE FOR GROUP II-A

Fig. 16 The behavior of group II-A

Fig. 17 Load-ovalisation curves for FEM (II-A-01, II-A-02, II-A-06, II-A-10 and II-A-14)

As for model (II-A-01), Fig.16 (a) shows that there is a good convergence between the deformed shapes of the test carried out by Choo et.al and the deformed shape obtained from the FEM. As in both (test and the FEM) two significant buckles appears in the chord both sides accompanied with clear ovalisation in the chord upper half. These two buckles decreased after stiffening the joints (as per model II-A-02) and the chord became fully yielded as shown in Fig.16 (b). While these two buckles disappeared after stiffening the joints (as per model II-A-06 and II-A-10) and the chord became fully yielded as shown in Fig.16 (c, d). The behavior of model II-A-14 is clear in Fig.16 (e) which shows that the deformed shape is almost as that of model II-A-02 but chord cross section is fully yielded and the yielded zone extended more than that in model II-A-02.

Fig.17 shows that all the joints plotted in the curve is governed by the ovalisation limit except the joint with ID II-A-06 and II-A-10. Thus, it is clear that increasing the stiffening elements thickness has effect on decreasing the joint ductility but not as the significant effect of increasing the radial flange diameter. Also it is seen in the curves that FEM II-A-02 and II-A-14 are ductile joints, but the capacity and the ductility of II-A-14 is larger than that of II-A-02 because increasing the additional pipe length increased the plastic zone limit.

f. THE DEFORMED SHAPE AND FAILURE MODE FOR GROUP II-B

Fig. 18 The behavior of group II-B

Fig. 19 Load-ovalisation curves for FEM (II-B-01 and II-B-02)

The deformed shape of model (II-B-01) is similar to that provided by Choo et.al as clear in Fig.18 (a) the chord is subjected to significant ovalisation in the chord upper half accompanied with severe chord plastification. Stiffening that joint with the proposed technique following the geometry of model (I-B-02) leads to brace tensile yielding which means joint full capacity occurred as shown in Fig.18 (b). In Fig.19, it is seen that the failure mode of FEM II-B-02 is a ductile failure as this joint is governed by brace tensile yielding as mentioned. Also it shows that by applying the proposed technique to FEM II-B-01, the joint capacity of II-B-02 almost reached the peak load of joint II-CB-01 that occurred at large value of ovalisation which shows the stiffening efficiency

g. THE DEFORMED SHAPE AND FAILURE MODE FOR GROUP II-C

Fig. 20 The behavior of group II-C

Fig. 21 Load-ovalisation curves for FEM (II-C-01 and II-C-02)

Significant ovalisation in the chord upper half appeared in model II-C-01 accompanied with severe chord plastification which is clarified in Fig.20 (a) after adding the stiffening components to the joint following the geometries of model II-C-02 the chord became fully yielded among the total cross section as shown in Fig.20 (b) which means reaching the joint full capacity. Fig.21 clarifies that the FEM II-C-02 is governed by the peak load and not the deformation limit that was governing II-C-01. Also it shows that by applying the proposed technique to FEM II-C-01, the joint capacity of II-C-02 almost reached the peak load of joint II-C-01 that occurred at large value of ovalisation which shows the stiffening efficiency.

h. THE DEFORMED SHAPE AND FAILURE MODE FOR GROUP II-D

Fig. 22 The behavior of group II-D

Fig. 23 Load-ovalisation curves for FEM (II-D-01 and II-D-02)

In FEM (II-D-01) the chord is fully yielded without adding additional stiffeners (as shown in Fig.22 (a)) which means that the joint was able to reach the maximum capacity and that is why the gain in group (II-D) was limited when compared to the joints of the other groups of category II. Fig.23 clarifies that the FEM II-D-02 is governed by the peak load and not the deformation limit that was governing II-D-01. Also it shows that by applying the proposed technique to FEM II-D-01, the joint capacity of II-D-02 almost reached the peak load of joint II-D-01 that occurred at large value of ovalisation which shows the stiffening efficiency.

6. PARAMETERS EFFECT AND DISCUSSIONS

a. THE RADIAL FLANGE DIAMETER-TO- CHORD DIAMETER RATIO (d_s/d_o) EFFECT

Fig.24. shows that the CHS T-joint compressive capacity increases with the increasing of the radial flange diameter, and also it shows that for the same value of (d_s/d_o) the gain is much bigger with smaller value of β . For example for group I-B (which has smallest $\beta= 0.28$), the gain reached 254.7% at (d_s/d_o) equals to 1.4. While as for group I-D (which has largest value of $\beta=0.74$), the gain reached 62.1% also at (d_s/d_o) equals to 1.4. This shows that (d_s/d_o) is more efficient with smaller value of β .

For group I-B the (d_s/d_o) enhanced the joint capacity until the brace reached its axial capacity. For group I-C, I-D, the gaining was in progress until reached the plastic moment of the chord, as such the joint achieved the maximum gain.

Fig.24. Effect of (ds/do) on the gain in joint capacity of category I

In case of tension loading, the effect of (ds/do) is presented by Fig.25. Which shows that in groups I-A, II-A, the improvement happened to the CHS T-joints with tensile brace is lesser than that with compressive brace. The stiffening enhanced the T-joint in group II-B until the brace reached its axial capacity, but as for groups II-A, II-C and II-D the gain was increasing until the chord reached its plastic moment.

Fig.25. Effect of (ds/do) on the gain in joint capacity of category II

b. THE STIFFENING ELEMENTS THICKNESS TO THE CHORD THICKNESS RATIO (t_s/to) EFFECT

The capacity of CHS T-joints either with compressive or tensile brace is directly proportional to (t_s/to) values, but the gain in joints subjected to compression is larger than that subjected to tension as shown in Fig.26 and Fig.27.

T-joints subjected to compression load with β equals to 0.28, the gain reached 195.1%. While for β equals 0.74, the joint capacity is increased by 62.1% which is also valuable gain.

For groups I-D, II-C, II-D, the joint was able to sustain load that leads to the chord plastic moment. While in group II-B, the capacity increased until reaching brace axial strength.

Fig.26. Effect of (ts/to) on the gain in joint capacity of category I

Fig.27. Effect of (ts/to) on the gain in joint capacity of category II

c. The ADDITIONAL PIPE LENGTH TO THE BRACE DIAMETER RATIO (ls/db) EFFECT

It is obvious in Fig.28 that for the T-joints with compressive brace, the effect of (ls/db) at smaller values of β is much efficient than that at bigger values of β ; as the gain when $\beta = 0.28$ reached 127%, while at $\beta = 0.74$ the maximum gain is 70.1%

For group I-B, the gain decreases with the increasing of (ls) as the confinement caused by the strengthening elements is decreased due to increasing the distance between the radial hollow flanges.

Fig.29 shows that the proposed strengthening technique enhanced joint capacity, and it also increased the plastic moment of the chord which is clearly shown for groups II-C, II-D, but as for group II-B the brace reached the ultimate axial load after at (ls/db) equals to 1.5.

Fig.28. Effect of (l_s/d_b) on the gain in joint capacity of category I Fig.29. Effect of (l_s/d_b) on the gain in joint capacity of category II

7. PARAMETRIC EQUATION AND ITS ASSESSMENT

Based on the parametric study (of category I) shown in table 5, a parametric equation has been concluded to calculate the static capacity of CHS T-joints strengthened by the proposed technique.

It is essential to note that some models in category I, the CHS T-joint reached its capacity due to global failure in the connection members -chord reached the plastic moment or brace reached the axial capacity-. These models have been excluded from the regression analysis. Also it is clear in table 5 that as (l_s/d_b) increases than (2) the strengthening technique efficiency decreases; thus the models with ($l_s/d_b \geq 2$) have been excluded from the regression analysis. So it is recommended to use (l_s/d_b) from $1.1 \rightarrow 2$ which almost have the same effect as shown in table 5 and in Fig.28.

$$P_s = P \times \alpha \quad \text{Eq. 2}$$

The magnification factor (α) in (Eq. 2) is determined by parameters (d_s/d_o), (t_s/t_o) and (β) using equation (Eq. 3).

$$\alpha = 1.2 \left(\frac{d_s}{d_o} \right)^{1.5} \cdot \left(\frac{t_s}{t_o} \right)^{0.45} \cdot \left(\frac{l_s}{d_b} \right)^0 \cdot (\beta)^{-0.35} \quad \text{Eq. 3}$$

The capacity of the unreinforced CHS T- joints (P) is calculated using the design code (CIDECT –design guide 1) that cover the design of such connection. The equation proposed by CIDECT to calculate the capacity of unreinforced T-joint, is based on the capacity of T-joints subjected to compressive loading. CIDECT mentioned that in- design guide 1 “part 4.2”- which stated that “*The resistance is based on the strength under brace compression loading, although this can also be used for brace tensile loading. The ultimate resistance under tensile loading is usually higher than that under compressive loading. However, it is not always possible to take advantage of this additional strength due to larger deformations or premature cracking*”. The strength of the stiffened T-joints is calculated by multiplying the capacity of the unstiffened joint proposed by CIDECT times the magnification factor (α). Thus, the regression analysis is performed based on models of category I where the chords are subjected to compressive brace loads.

The applicability of (Eq. 3) is valid when the following ranges are satisfied:

$$1.1 \leq \left(\frac{ds}{do}\right) \leq 1.5 \qquad 0.75 \leq \left(\frac{ts}{to}\right) \leq 1.75 \qquad 1.1 \leq \left(\frac{ts}{db}\right) \leq 2 \qquad 0.28 \leq (\beta) \leq 0.74$$

The assessment of (Eq. 3) has been carried out by comparing the static capacity of strengthened CHS T- joints obtained from the FEM and with that calculated using (Eq. 2) and (Eq. 3) and that is illustrated in Fig.30.

Fig.30. Comparison between the calculated and the numerical results

In order to evaluate precisely the parametric equation, the relative error, the average relative error, the relative standard deviation and the average relative standard deviation are obtained and here is the corresponding values:

The average relative error = 8.27 %

The relative standard deviation = 9.26 %

The average relative standard deviation = 9.11 %

These values reflect the reliability and the accuracy of the proposed parametric equation to calculate the static capacity of CHS T- joints strengthened by the proposed technique.

8. CONCLUSIONS

In this study a strengthening technique was proposed for CHS T- joints either subjected to tension or compression load cases. Finite element modeling were performed after calibration with independent experimental results. Based on the results obtained from 104 models of CHS T-joints strengthened with the proposed technique, the following conclusions are drawn:

- a. By using the proposed strengthening technique, the joint capacity enhanced significantly as in some cases the brace axial capacity or chord plastic moment was reached; which means maximum gain has been occurred for those cases.
- b. (d_s/d_o) is more effective in the proposed strengthening technique at smaller values of chord diameter to brace diameter ratio (β).
- c. Increasing (t_s/t_o) is efficient for all values of β and for both brace load cases (tension/compression).
- d. For CHS T-joints with compressive axial brace, decreasing the distance between the two additional flanges (l_s) with relative to the brace diameter (d_b) leads to high gain values.
- e. For CHS T-joints with tensile axial brace, the joint capacity is directly proportional to the distance between the two additional flanges with respect to the brace diameter (l_s/d_b).
- f. (d_s/d_o) is the most effective parameter for CHS T-joints subjected to compressive axial brace.
- g. (l_s/d_b) is the most effective parameter for CHS T-joints subjected to tensile axial brace.
- h. The efficiency of the CHS T-joint increased as the difference between the tensile capacity of the joint and that of the compressive joint decreased.

9. NOTATION

The following symbols are used in this paper:

d_o = outer diameter of the chord;

t_o = thickness of the chord;

l_o = length of the chord;

E_o = young's modulus of the chord;

$f_{y,o}$ = yield stress of the chord;

d_b = diameter of the brace;

t_b = thickness of the brace;

l_b = length of the brace;

E_b = young's modulus of the brace;

$f_{y,b}$ = yield stress of the brace;

β = diameter ratio d_b / d_o ;

- 557 2γ = chord diameter to thickness ratio d_o/t_o
 558 d_s = radial flange diameter
 559 t_s = stiffening elements thickness
 560 l_s = additional pipe length
 561 P_s = calculated strengthened CHS T-joint capacity
 562 P = calculated unreinforced CHS T-joint capacity
 563 α = magnification factor
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565 10. RECOMMENDATION FOR FUTURE RESEARCH

566 Further studies can be carried out by changing the weld between the steel elements from full penetration (as
 567 followed in this study) into fillet weld. For such study, it is recommended to follow the suggestion provided by (Kim
 568 et al. 2015) for the improved modelling technique including fillet welding.

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