Title	Residual stress of high strength steel box T-joints Part 1 : experimental study
Author(s)	Lee, Chi King; Chiew, Sing Ping; Jiang, Jin
Citation	Lee, C. K., Chiew, S. P., & Jiang, J. (2014). Residual stress of high strength steel box T-joints. Journal of Constructional Steel Research, 93, 20-31.
Date	2013
URL	http://hdl.handle.net/10220/19806
Rights	© 2014 Elsevier Ltd. This is the author created version of a work that has been peer reviewed and accepted for publication by Journal of Constructional Steel Research, Elsevier Ltd. It incorporates referee's comments but changes resulting from the publishing process, such as copyediting, structural formatting, may not be reflected in this document. The published version is available at: [DOI: http://dx.doi.org/10.1016/j.jcsr.2013.10.003].

Residual stress of high strength steel box T-joints

Part 1: Experimental study

*C. K. Lee, S. P. Chiew and Jin Jiang

School of Civil and Environmental Engineering
Nanyang Technological University
50 Nanyang Avenue, Singapore 639798

*Email: ccklee@ntu.edu.sg

ABSTRACT

In Part 1 of this study, an experimental investigation on the residual stress distributions near the weld toe of high strength steel box section T-joints is conducted. Two specimens fabricated by welding at ambient temperature and at a preheating temperature of 100°C were studied. The effects of preheating on the residual stress distribution near the weld toe of the T-joints were investigated by applying the standard ASTM hole-drilling method. A study was also conducted to evaluate the corner effect of the welding and the brace-to-chord width ratio of the box section T-joint on the residual stress distribution near the weld toe of the T-joint.

Keywords: Welded residual stress, high strength steel, box section T -joints, The ASTM hole-drilling method

1. INTRODUCTION

Recently there has been an increasing interest in the use of high strength steel (HSS) with yield strength larger than 460MPa in structural engineering. However, the stress-strain behavior of HSS is different from mild steel such that HSS exhibits reduced ductility due to strain hardening after yielding. In general, residual stress should depend on the restraint of welds and base metal during the cooling phase and properties such as the Young's modulus of base metal and the welding materials [1]. Residual stress due to welding in HSS could be more serious than that in mild steel and might have a negative impact on its fatigue performance. Hence, a good understanding of residual stress distribution around the welded joint is important when assessing the performance of HSS structures.

Different from a plate-to-plate joints in which welding is carried out only along the chord width direction [2-3] and rectangular hollow section joints in which welding is only carried out along the joint connecting the chord and the brace [4-5], the fabrication procedure of HSS box joint are more complex. As HSS with high yield strength of 690MPa is often supplied only in the form of steel plates, welding is required for both the box section fabrication step and the joint formation step. Hence, both the chord and the brace box sections are first fabricated by assembling four HSS plates together. Therefore, residual stress will be generated in the chord and brace sections *before* they are welded together. As a result, the final residual stress field in the joint will consist of two parts, namely the residual stress generated during the fabrication of the brace and chord box sections and the residual stress generated during the fabrication of the joint. While the combination of the cross-sectional characteristics of welded box section and the existence of high tensile residual stress generated at the welded corners of the box section could strengthen the member when used as a column, depends of the brace-to-chord width ratio, these two residual stress fields may interfere each another and complicate the residual stress distribution around the joint.

Many investigations on welding residual stress distribution of hollow sections and tubular joints can be found in the literatures. Wikander et al. [6] carried out experimental and numerical investigations of a welded D-shaped cross section. Payne and Porter-Goff [7] conducted an experimental study on the residual stress distributions in welded tubular T-nodes. Jang et al. [8] analyzed the residual stress distribution near the weld toe of a circular T-joint. Acevedo and Nussbaumer [9] studied the residual stress of welded tubular K-joint under fatigue loads. Recently Wang et al [10], assessed the residual stresses in weld box sections fabricated using the Q460 steel with nominal yield strength of 460MPa. In addition, their study found that the hole drilling method should be preferred to measure residual stresses near the heat affected zone while the sectioning method should be preferred for residual stress measurements of structural steel members. One common characteristic of their works is that they only studied the residual stress caused by joint welding as their joints are made of mild steel rolled hollow sections. In fact, experimental data related to the study of residual stress for welded HSS box section joints are almost absent. Therefore, in order to investigate and understand the residual stress distributions caused by welding during the fabrication of HSS box section T-joints, a carefully planned experimental study and a corresponding numerical study are conducted and the results obtained are reported two parts. In this paper, the experimental results obtained will be reported while the numerical modeling procedure and the numerical simulation results will be reported in Part 2 [11].

In the experimental study presented in this paper, two HSS box section T-joints with identical dimensions were fabricated to investigate the welding residual stress distributions and the effect of preheating. The first specimen was welded at ambient temperature (the ambient temperature specimen) while all welding of the second specimen was conducted with preheating to 100°C (the preheated specimen). For both specimens, the residual stress distributions near the chord weld toe of the joints were measured by the American Society for Testing and Materials (ASTM) incremental hole-drilling method [12].

2. SPECIMEN SPECIFICATIONS

2.1 Material properties of HSS steel plates and welding electrode

The two HSS box section T-joints investigated in this study were made of RQT701 HSS steel plate with minimum yielding stress of 690MPa. They were fabricated using flux-cored arc welding (FCAW) welding. During the welding process, the American Welding Society (AWS) standard [13] was followed to obtain full penetration weld. In order to evaluate the impact of preheating, preheating to a suitable pre-determined temperature of 100°C [14] was carried out before welding for one specimen while for another joint; all welding was done at ambient temperature. The RQT701 HSS plate used in this study [15] comply with the EN 10025-6 grade S690 specification [16]. In order to determine the material properties of the RQT701 HSS steel plate and to provide accurate inputs for the numerical simulations conducted in Part 2 [11], coupon tests at normal and elevated temperature were performed by following the relevant standard [17]. Table 1 gives the HSS plate's mechanical properties at room and elevated temperatures. In order to prevent hydrogen cracking for the HSS plates, an ultra-low hydrogen and moisture resistant type covered electrode for low temperature service, OK Tubrod 15.09 [18] was used. It is formed in cored wire for welding high strength steel with minimum yield strength of 690MPa and with a diameter of 1.2mm. Table 2 lists the welding parameters employed in this study.

2.2 Fabrication of the specimens

Fig. 1 shows the dimensions of the HSS box section T-joints which were fabricated by using 12mm thick RQT701 HSS plates. The width of the chord and the brace are equal to 300mm and 200mm, respectively. The fabrication of the joints was divided into two stages. The first stage is to build up the chord and brace box sections from the HSS plates (Fig. 2(a) to Fig. 2(c)). The second stage is to assemble the chord and the brace box sections to form the final T-joint by carrying out welding along the joint (Fig. 2(d) and Fig. 2(e)). In the first stage, the RQT701 steel plate was cut into several strips (Fig. 2(a)). Two sizes of steel strips (3000mm×300mm×12mm, 2200mm×200mm×12mm) were used respectively for the chord and brace boxes. After that, the brace and chord boxes were assembled Fig. 2(b). In order to sustain the molten weld during the box section formation, four mild steel backing plates (3000mm×50mm×10mm) were prepared and they were connected to the chord boxes by spot welding (Fig. 2(c)). Similar preparation procedure was also employed for the brace box sections. In order to prevent large deformation during the welding, two retaining plates were welded to the box at 40mm from the ends by spot welding (Fig. 2(c)). After these preparations were done, molten weld was added on the groove to form the brace and the chord sections until full penetration weld was obtained. In the second stage, the HSS box section T-joint was formed by welding the brace and the chord together (Figs. 2(d) and 2(e)). Finally, three 35mm thick mild steel back plates (Fig. 2(f)) were welded to the two ends of the chord and the end of the brace. Similar to the previous studies involving mild steel structural hollow section joints [19,20], this allows the joint to be attached to the test rig for further static and dynamic tests after the residual stress study was completed [21].

Fig. 3 shows the layout and welding sequence of the brace and chord box sections. Welding passes 1 to 4 were sequentially added at four corners of the box sections. After that, welding was carried out at each corner one by one until full penetration weld profile was obtained. The box sections were fabricated in this manner so that they can be heated evenly to reduce deformation caused by the welding. Fig. 4 shows the welding sequence and profile for the final HSS box section T-joint.

2.2.1 Fabrication of the box sections

The welding processes for the ambient temperature specimen and the preheated joint are different. For the former one, the weld filler was gradually added at the reserved groove without pause until a complete weld pass was created. However, for the preheated joint, one complete weld pass composes of six welding steps for the chord box hollow sections (Fig. 5(a)). The chord box section was divided into 3 parts with same length of 1m. Preheating was first carried out for Section 1 (Step 1 in Fig. 5(a)). After the target temperature (100°) was achieved, the weld filler was added into the groove (Step 2 in Fig. 5(a)). After that, preheating and welding were carried out for the second section (Steps 3 and 4 in Fig. 5(a)). Similar procedure was repeated for the third section to form a complete weld pass. For the shorter brace box section, similar procedure was applied except that it was divided into 2 sections.

2.2.2 Fabrication of the joints

Fig. 6 shows the welding direction adopted at the chord-brace intersection for both the ambient temperature and the preheated specimens. When forming the joints, one complete weld pass around the joint intersection was composed of four welding steps. The first step was started from Point 1 and ends at Point 7, covering side B1. The second step was from Point 7 to Point 13 (sides B2) and the third step was from Point 13 to Point 19 (side B3). Finally, to cover side B4, the weld filler was added from Point 19 and returned back to Point 1. Note that for every pass, welding was started at Point 1. Two considerations are taken into account for such welding layout and sequence. The first one is to control the welding residual stress at the corners (the distance from Point 1 and Point 2 is 36mm). When the molten weld is gradually added from Point 1 to Point 2, corner *a* would be heated to an elevated temperature and it means that there were some preheating near the corner. The second reason is to make it easier for the welder to complete the welding. By selecting Point 1 as the starting position for every weld pass, welding would not be paused at the corners of the joints and the welder could adjust his position to achieve a continuous welding without long breaks. The same welding process was used for the total 14 weld passes (Fig. 4) until full penetration weld profile was achieved.

For the preheated specimen, areas close to all weld paths were heated up to 100°C before welding. It is required that the area within 50mm [14] from the chord weld toe should reach a preheating temperature of 100°C before the weld pass. Temperature chalk was employed to ensure that the designated preheating temperature was reached and maintained before every weld pass in case the welding was paused for a short time in order to allow the welder to take a break. After the box sections formation and joint welding were completed, ultrasonic tests were carried out for all welding profiles to ensure the welding quality.

2.3 Residual stress measurement scheme

2.3.1 The modified drilling guide

Similar to the previous tests conducted for HSS plate-to-plate joints [2], the modified RS-200 milling guide was employed to measure the residual stress using the hole-drilling method through positioning and drilling of a hole in the center of a special strain gauge rosette [12]. The modified milling guide allows measurement of residual stress at point as close as 5mm from the chord weld toe. In the drilling process, the strain readings were recorded for every 0.05mm depth until an 1mm hole with diameter of 1.6mm was obtained. The strain readings at 20 different depths are recorded to find the distribution of residual stress along plate depth. Before the drilling, the strain gauges were attached on the surface of the chord box by using an optical microscope so that the error of the alignment is less than 0.025mm. During the drilling, an air turbine is used to drive the tungsten cutter to rotate at very high speed (up to 400000 rpm) to minimize the machine-induced residual stresses at the hole boundary. With this careful precaution, it is believed that the relative error of the residual strain measured should be less than 5% [22].

2.3.2 Residual stress measurement schemes and computations

For the preheated specimen, 24 monitoring points (Point 1 to 24 in Fig. 7) around the joint were selected with strain gauge rosettes attached to capture the residual stress distribution near the chord weld toe. Points 1 to 18 are located 10mm from the weld toe while Points 19 to 24 are located 15mm from the chord weld toe. Larger distance was chosen for Point 19 to Point 24 in order to leave enough space to attach alternating current potential drop (ACPD) probes [19,20] around corner *d* for the subsequent fatigue tests [21]. Beside these 24 monitoring points around the intersection, another group of strain gauges/drilling points was added at 20mm from the chord weld toe at corners *a*, *b* and *c* and 25mm at corner *d* so that linear interpolation method can be employed to estimate the residual stress at the weld toe near the corners (Fig. 7).

For the ambient temperature specimen, besides the strain gauges which were positioned at the same points as the preheated specimen, four additional monitoring points (Points 25-28) were added near Point 12 with spacing of 40mm to evaluate the residual stress variation with respect to the distance from the weld toe at the middle section of the joint. Furthermore, another four points (Points 29 to 32 in Fig. 7) were included on the top surface of the chord box section to measure the residual stress near the edge of the chord wall. Note that these four points are located far away (≥150mm) from the joint so that the residual stress generated during the welding of the joint could not affect them. Points 29, 30 and Points 31, 32 are on the same straight line with Points 16 to 18 and Points 4 to 7, respectively.

After the strain readings at different hole depths were measured, the procedure recommended by the in the ASTM [12] were employed for residual stress computation. In the following sections, when a residual stress value is mentioned for a monitoring point, this value is in fact the arithmetic mean based on 20 different measurements within the 1mm hole. Furthermore, the definitions of transverse, longitudinal and principle residual stress directions at different monitoring points are shown in Fig. 8. Note that the transverse direction and longitudinal direction are perpendicular and parallel to the welding travelling direction (welding path), respectively. In addition, tensile stress is considered as positive and the angle θ is defined as the deviation angle between the principle residual stress and the transverse residual stress.

3 EXPERIMENTAL RESULTS

3.1 Results from the preheated joint

Fig. 9 shows the distribution of the maximum residual principle stress and its direction at measurement points 10/15 mm from the chord weld toe for the preheated specimen. It can be observed that the magnitude of residual stress is much higher near the corners than the other points. Another finding is that the residual stresses along sides B2 and B4 are higher than the residual stress along sides B1 and B3. For the principle stress direction, while shifting from the transverse direction appeared for most points, smaller shifts were found along sides B2 and B4 when comparing with sides B1 and B3. The residual stresses measured at points at 20/25mm from the chord weld toe at the four corners are shown in Fig. 10. In general, the principle residual stresses at 20mm/25mm are smaller than the corresponding values at 10mm/15mm. However, it should be noticed that at Points 3, 4, 7, and 21, the principle stresses at 20mm/25mm from the chord weld toe are higher than that at 10/15mm. Figs. 11 and 12 respectively show the distributions of transverse residual stress at 10/15mm and 20/25mm (at the four corners only) from the chord weld toe. Fig. 11 shows that the transverse stress along sides B1 and B3 is significantly smaller than that along sides B2 and B4. For residual stress at 20/25mm from the chord weld toe at the four corners, at Point 21 compressive residual stress was found. In general, when comparing with the residual stress at 10/15mm from the chord weld toe, the magnitude of residual stress at 20/25mm is lower. However, there are some exceptions such as Points 4 and 7, where larger residual stress can be found at 20/25mm. The longitudinal residual stresses for the preheated joint are shown in Figs. 13 and 14 (at the four corners only). In general, the magnitude of longitudinal residual stress is lower than the transverse residual stress.

Since the residual stress distributions at 10/15mm and 20/25mm positions from the chord weld toe were obtained, linear interpolation method was employed to estimate residual stresses there. Only linear interpolation method was used as there was not enough space to attach a third layer of strain gauges along sides B1 and B3. Fig. 15 shows the comparison between the transverse and longitudinal residual stresses and it can be seen that the transverse stress is much higher than the longitudinal component.

3.2 Results from the ambient temperature specimen

Fig. 16 shows the distribution of the maximum principle stress and its direction for the ambient temperature specimen at 10/15mm from the chord weld toe. Note that the magnitudes of residual stress at corners *b* and *c* are higher than other points. Similar to the case of the preheated specimen, the residual stresses at sides B2 and B4 are higher than that along sides B1 and B3. Furthermore, shifting in principle stress direction is higher near the corners than along the four sides. Fig. 17 shows the maximum principle stress and its direction at 20mm/25mm from the chord weld toe around the four corners. Note that for Points 4, 8, 16 and 20 which are located along sides B1 and B3 and are close to the edge of the chord wall (Fig. 7), their principle stresses at 20/25mm points are higher than those at 10/15mm points.

Figs. 18 and 19 respectively show the distributions of the transverse residual stresses at 10/15mm and 20/25mm (at the four corners only) from the chord weld toe. When comparing with the residual stress along sides B2 and B4, the transverse residual stresses along sides B1 and B3 are lower. However, for Points 8, 9, 16 and 20, the transverse residual stresses at 20/25mm are higher than that at 10/15mm. For the longitudinal residual stress of the ambient temperature specimen, it is again found that they are much smaller than the transverse component and therefore their detailed plots are not shown here.

Fig. 20 shows distributions of residual stresses at the chord weld toe obtained from linear interpolation for the ambient temperature specimen. Similar to the case of the preheated joint, the transverse stress is higher than the longitudinal stress. Tensile transverse residual stress can be found at all points. Fig. 21 shows the relationship between the transverse residual stress and the distance from the chord weld toe (measured at Points 12, 25 to 28). From Fig. 26, it is clear that the transverse residual stress decreases quickly as the distance from the weld toe increases and eventually becomes compressive.

4 ANALYSES AND DISCUSSION

4.1 Preheating effect

The comparison of the transverse residual stress distributions at the chord weld toe between both specimens are given in Fig. 22. Fig. 22 indicates that preheating effectively reduced the transverse residual stress for the HSS box section T-joint tested in this study. Such reduction due to preheating was found to be most obvious nears the corners (Points 2, 10 and 14 in Fig. 27). This phenomenon can be ascribed to the different heating and cooling rates attained during the welding process that are influenced by the joint geometry and the welding variations, which have been validated by Lee et al.[2-3]. However, Points 20, 21, 22 (Corner *d*) are exceptional and preheating failed to reduce the residual stress significantly. Towards this end, three possible reasons may explain this phenomenon. The first reason is uneven preheating which could generate unexpected high temperature gradients, which could increase the cooling rate and could eventually lead to higher residual stress at some parts of the preheated joint. The second reason is residual stress interference which could significantly change the distribution of residual stress (details will be discussed in the next section). The third reason is the extrapolation method adopted for estimating the residual stress at the chord weld toe. It was found by Lee et al. [2-3] that the relationship between the residual stress and the distance from the weld toe could be highly nonlinear. However, due to experimental limitations, there was not enough space to attach a third layer of rosettes along sides B1 and B3. As a result, only linear interpolation could be employed and it may introduce more error when estimating the residual stress when comparing with the more accurate quadratic interpolation method [2, 19, 20].

4.2 Interference of residual stresses

As the sizes of the chord and brace are 300mm and 200mm respectively, it is found that the distance between the chord weld toe for sides B1 and B3 to the edge of chord wall is less than 40mm. Such a short distance may result in interference between the residual stress fields generated during the formation of the chord box section and the welding along the joint. This could possibly explain the observation that for both specimens, the residual stress along sides B1 and B3 are smaller than the residual stress along sides B2 and B4. This also explains the observation that residual stress is higher at some points at 20/25mm from the chord weld toe than those at 10/15mm. Obviously, the interference effect is affected by the distance between the chord weld toe and the edge of the chord wall and will be reduced as such distance increases. Hence, in Part 2 of this study [11], several numerical models will be created to investigate such interference effect. Note that besides such residual stress interference effect, another possible cause for the higher residual stress along sides B2 and B4 is the difference in the natural cooling rates at different parts of joint due to the joint geometry. Again, such effect will also be investigated in Part 2 of this study.

In order to confirm the presence of interference effect, four strain gauges (Points 29, 30, 31 and 32, Fig. 7) were attached to the ambient temperature specimen to measure the residual stress close to the edge of the chord wall but far away from the joint. The transverse residual stresses for Points 29, 30, 31 and 32 are respectively 212.8MPa, 237.2MPa, 187.6MPa and 194.6MPa. When comparing with the corresponding results at Point 4 to Point 8 and at Point 16 to Point 20 (Fig. 18), the stress at Points 29, 30, 31 and 32 are obviously higher. Therefore, it can be concluded that part of the residual stress near the chord weld toe along sides B1 and B3 were actually cancelled due to the interference between the residual stress fields. In fact, it is found that such results can be reproduced in the numerical study conducted in Part 2.

4.3 Corner effects

From Figs. 9 to 14 and Figs. 16 to 19, it can be seen that for both specimens the residual stress at the corners is higher than that at other positions. Such "corner effect" seems to be more obvious for points at 10/15 mm from the weld toe than those points at 20/25mm from the weld toe. For example, for the preheated specimen, the maximum residual stress is found at Point 22 (Fig. 9) where the principle stress is 582.4MPa. For the transverse residual stress, similar conclusion can be obtained from Fig. 11. However, for the residual stress in the longitudinal direction, as shown in Fig. 13, it can be seen that such corner effect is not very remarkable.

4.4 Comparison with residual stresses reported in other study

Table 3 summarize and comparing the residual stresses measured in some previous similar studies involving rolled and welded mild steel parts [1], tubular K joint [9] and welded box section [10]. From the Table 3, it can be seen that in terms of absolute magnitude, with the exception for hot rolled section for which the magnitude of residual stress is well known to be much smaller than all welded connections, the residual stress ranges obtained in this study are consistent with the other test results. However, for the normalized range with respect to the yield or proof stress, the advantage of HSS can be seen clearly. Due to its intrinsic high yield strength, the maximum normalized residual stress of HSS (60%) is lower than that of the Q460 steel (79%) and than that of mild steel (93%).

5 CONCLUSIONS

In this paper, results obtained from an experimental study aimed to investigate the welding residual stress distributions along the chord weld toe of high stress steel (HSS) box section T-joints are presented. Two specimens fabricated by welding performed at ambient temperature and at a preheating temperature of 100°C are studied. The ASTM hole-drill method was employed to measure residual stress at critical locations of the joint near the chord weld toe. It is found that preheating is beneficial and can effectively reduce the magnitude of residual stress. For the residual stress distributions, it is found that residual stress at the corners of the joint are higher than that at other positions for both specimens and the transverse component is the dominating residual stress component. In addition, for the box section T-joints studied, interference between the residual stress fields formed during the fabrication of the box sections and that during the final welding of the T-joint is observed.

In Part 2 of this study, the results obtained in this paper will be employed to validate the 3D numerical model employed for the simulation of the welding process. After the accuracy and reliability of the numerical model are confirmed, it is then employed to carry out a parametric study to investigate the influences of different welding parameters including the preheating temperature, the brace-to-chord width ratio, the welding speed and the joint angle on the welding residual stress near the weld toe of HSS box section T-joints.

Acknowledgment: The financial support of the Regency Steel Asia to the authors is gratefully acknowledged. The helps from the Yongnam Pte Ltd., Singpaore, for the fabrication of the test specimens are also appreciated.

REFERENCES

[1] R. D. Ziemian (Editor-in-Chief), Guide to Stability Design Criteria for Metal Structures 2010, 6th edition, John Wiley and Sons, 2010

[2] C. K. Lee, S. P. Chiew and Jin Jiang., 2012, Residual stress of welded high strength steel thin-walled plate-to-plate joints Part 1: Experimental study, Thin-Walled Structures, Vol. 56, pp. 103-112.

[3] C. K. Lee, S. P. Chiew and Jin Jiang., 2012 Residual stress of welded high strength steel thin-walled plate-to-plate joints Part 2: Numerical modeling, Thin-Walled Structures, Vol. 59, pp. 120-131.

[4] S. P. Chiew, S. T. Lie, C. K. Lee and Zhiwei Huang., 2004, Fatigue Performance of Cracked Tubular T Joints under Combined Loads. I: Experimental, Journal of Structural Engineering, Vol. 130, pp. 562 - 571

[5] S. P. Chiew, S. T. Lie, C. K. Lee and Zhiwei Huang, 2004, Fatigue Performance of Cracked Tubular T Joints under Combined Loads. II: Numerical, ASCE Journal of Structural Engineering, Vol. 130, pp. 572 - 581.

[6]. L. Wikander, L. Karlsson, M. Nasstrom and P. Webster, 1994, Finite element simulation and measurement of welding residual stresses, Modelling and Simulation in Materials Science and Engineering, Vol. 2, pp. 845-864.

[7] J. G. Payne and R. F. D. Porter-Goff, 1986, Experimental residual stress distributions in welded tubular T-nodes. The Institution of Mechanical Engineers, C134/86, pp. 109-116.

[8] G. C. Jang, K. H. Chang, and C. H. Lee, 2007, Characteristics of the residual stress distribution in welded tubular T-joints. Journal of Mechanical Science and Technology, Vol. 21, pp. 1714-1719.

[9] C. Acevedo and A. Nussbumer, Influence of welding residual stress on stable crack growth in tubular K-joints under compressive fatigue loadings. 13th International Symposium on Tubular Structures, Hong Kong, 2010, pp. 557-65.

[10] Y. B. Wang, G. Q., Li, S. W. Chen, 2012, The assessment of residual stress in welded high strength steel box sections, Journal of Construction Steel Research, Vol. 76, pp93-99

[11] C. K. Lee, S. P. Chiew and Jin Jiang, Residual stress study of welded high strength steel box section T-joints, Part 2: Numerical modelling. Submitted to the Journal of Construction Steel Research for publication.

[12] American Society for Testing and Materials (ASTM), Standard test method for determining residual stresses by Hole-Drilling Strain-Gage Method (E837-08), 2008, ASTM International: West Conshohocken, US.

[13] American Welding Society (AWS), Structural Welding Code-Steel (AWS D1.1), 2008, American Welding Society: Miami, US.

[14] BSI, Welding Recommendations for welding of metallic materials, in Part 2, Arc welding of ferritic steels, 2011, London, UK.

[15] Corus Construction & Industrial. RQT701 Data Sheet, Scunthorpe, North Lincolnshire, Britain, 2006.

[16] Hot rolled Products of structural steels. Part 6: Technical delivery conditions for flat products of high yield strength structural steels in the quenched and tempered condition. London, British Standards Institution, 2004

[17] B.S.I., Tensile testing of metallic materials Part 5: Method of test at elevated temperatures, 1992, British Standard Institute (BSI), London, UK.

[18] ESAB, Welding Handbook, Consumables for manual and automatic welding, Eighth edition.

[19] S. P. Chiew, C. K. Lee, S. T. Lie and H. L. Ji, 2007, Fatigue behaviors of Square-to-Square Hollow Section T-joint with corner crack. I: Experimental studies, Engineering Fracture Mechanics. Vol. 74, pp. 703 – 720

[20] S. P. Chiew, C. K. Lee, S. T. Lie, and T. B. N. Nguyen, 2009, Fatigue study of partially overlapped circular hallow section-joints, Part 2: Experimental study and validation of numerical models, Engineering Fracture Mechanics. Vol. 76, pp. 2408-2428

[21] M. S. Zhao, S. P. Chiew and C. K. Lee, 2013, Fatigue behavior of rectangular built-up hollow section joint made of high strength structural steel S690, The proceeding of The Thirteenth East Asia-Pacific Conference on Structural Engineering and Construction (EASEC-13), School of Engineering, Hokkaido University, Japan.

[22] W. H. Wang, 1979, The alignment error of the hole-drilling method, Experimental Mechanics, Vol. 19 pp23-27