Post Weld Heat Treatment for High Strength Steel Welded Connections

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Abstract: In this study, experiments were conducted to investigate the effect of post-weld heat treatment (PWHT) on the reheated, quenched and tempered (RQT) grade S690 high strength steel welded connections. Firstly, the effect of PWHT on the mechanical properties after welding is investigated. It is found that the loss of both strength and ductility after welding could be serious but PWHT could able to improve the ductility of the affected specimens at the expense of strength. Secondly, four Y-shape plate-to-plate (Y-PtP) and nine T-stub RQT-S690 joints are fabricated to study the effect of PWHT on the residual stress level near the weld toe and the tensile behavior of the joints, respectively. The hold drilling tests reveals that PWHT is able to decrease the residual stress level near the weld toe significantly. The tensile test results show that proper PWHT could improve both the ductility and the maximum resistance while the reduction of plastic resistance can be kept in a negligible level. However, it is found that if the specimens are overheated, although the ductility could still be increased, the reduction of load carrying capacity was severe.

Response to Reviewers: For the respond to reviewers' comments, please kindly referred to the attached reply summary.

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Dear Prof. Parke,

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Post Weld Heat Treatment for High Strength Steel Welded Connections

M.S. Zhao, C.K. Lee and S.P. Chiew

Thanks for your email of 23 February 2016 regarding the reviewers' comments on the above paper. I am pleased to inform you that we have carefully answered all the questions from the reviewers. In addition, we also considered all the comments carefully, and all of them are taken aboard. Please find enclosed with this letter the following items for consideration:

- (1) A summary of our replies and amendments of the revised paper.
- (2) A copy of the revised manuscript with all the major changes corresponding to the questions and comments from the reviewers printed underlined.

Furthermore, we have also revised the manuscript very carefully to clear all typo and grammatical errors.

Should you have any problem regarding the paper, please do not hesitate to contact me directly.

All the best.

Yours truly,

Dr. M.S. Zhao

Highlights

- Effect of PWHT for RQT-S690 welded connections is investigated
- PWHT may improve the ductility at the expense of strength
- PWHT decreases the residual stress level near the weld toe significantly
- Over treatment jeopardize the load carrying capacity

Replies to comments from Reviewer 1

1. *Put increase the attention paid the use of Eurocode 3 Part 1-9, which is compulsory in Europe.*

Authors' reply: Eurocode 3 Part 1-9 is the standard for design of steel structures under fatigue. This study only focuses on the static behavior of the RQT-S690 material and T-stub joints subjected to PWHT. However, it is appreciated that the reviewer's reminder of possible fatigue issues and requirements. This topic can surely be studied in the future.

Amendments made: Attention to fatigue and Eurocode 3 Part 1-9 is given in the Introduction. Focuses of this study, i.e. static behavior, are justified and emphasized.

2. *Indicate more clearly that tensile tests are used.
How is the statistical evaluation of the test results undertaken to make it possible to compare the test results on test pieces with actual values of yield stress or 0,2% equivalent stress and the actual tensile strength to the design S-N curves mentioned in the code.*

Authors' reply: In this paper, only the results of those 6 specimens (presented in Table 3 and Fig. 7) are discussed. However, many other specimens are tested as well in order to investigate the influence of important test variables such as thickness, holding temperature, holding time and cooling rate. The results of these specimens are not shown in this paper, because these specimens are either not fully affected by the welding process (too thick) or are subjected to PWHT methods different from those mentioned in Phase II of this study. These test results can support and justify that the results shown in this paper are reliable and significant in statistical sense.

As mentioned in the reply to Question 1, the focus of this paper is the static behavior instead of fatigue. Not much attention is given to the possible fatigue issues and therefore the S-N curve is not mentioned either. Only the 0.2% equivalent strength and the actual tensile strength are analyzed as the characteristic strengths. However, the reviewers would like to thank the reviewer's input and reminder on the fatigue issue of HSS after PWHT and certainly this is an important topic that could be studied in the future.

Amendments made: Further explanation and justification of the tensile test program are given in section 3.3.

Replies to comments from Reviewer 2

1. *This paper provides a carefully prepared work on high strength steel material for post weld heat treatment and its effects on material mechanical properties. The results are valuable for application reference.*

One comment is on the results of the T-stub joint tests. The paper uses Eqn. (1) for evaluation of the theoretical resistance of the joint specimen, but does not state which values for f_y are adopted. Considering the previous part of the paper, I understand that this research obtained mechanical properties for RQT S690, AW and PWHT, but for the latter two, the results of material properties were those on or near HAZ. In the case of the T-stub joints, however, considering two plastic hinges near bolt holes are with a reasonable distance from the weld toe, do the authors suppose the mechanical properties to be the same as those for the HAZ, please explain?

Authors' reply: The authors thank the reviewers' appreciation sincerely. The value for f_y in Eqn. (1) is the nominal yield strength, as this equation is used to estimate the design plastic resistance of T-stub joints. Indeed the two plastic hinges near bolt holes are located at some distance from the weld toe. The authors supposed the mechanical properties in these two plastic zones are partially altered during welding and PWHT. Although the properties in these two zones may not be the same as those for the HAZ, the PWHT may still effective on improving the performance to some extent.

Amendments made: The definition of f_y in Eqn. (1) is added. To avoid confusion, the explanation in the reply is also added into section 4.1.

Post Weld Heat Treatment for High Strength Steel Welded Connections

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Abstract

In this study, experiments were conducted to investigate the effect of post-weld heat treatment (PWHT) on the reheated, quenched and tempered (RQT) grade S690 high strength steel welded connections. Firstly, the effect of PWHT on the mechanical properties after welding is investigated. It is found that the loss of both strength and ductility after welding could be serious but PWHT could be able to improve the ductility of the affected specimens at the expense of strength. Secondly, four Y-shape plate-to-plate (Y-PtP) and nine T-stub RQT-S690 joints are fabricated to study the effect of PWHT on the residual stress level near the weld toe and the tensile behavior of the joints, respectively. The hole drilling tests employed to study the residual stress reveal that PWHT is able to decrease the residual stress level near the weld toe significantly. The tensile test results show that proper PWHT could improve both the ductility and the maximum resistance while the reduction of plastic resistance can be kept in a negligible level. However, it is found that if the specimens are overheated, although the ductility could still be increased, the reduction of load carrying capacity was severe.

Keywords

Post-weld heat treatment; High Strength Steel; Welded Connections; Residual Stress; Tensile Behavior

1. Introduction

Heat input is essential in most discussions related to the process of welding in structural steel connections. Heat input during welding produces a variety of structural, thermal and mechanical effects into the heat affected zone (HAZ) such as expansion and contraction, metallurgical changes and compositional changes [1]. Steels are more significantly altered by the heat of welding than other metals. In particular, high strength steels including heat treatment or work hardened steels are the most sensitive types [2]. Researchers have shown that the welded quenched and tempered steel structures are accompanied by higher amount of residual stress than normal strength steel structures [3, 4], and the deterioration of mechanical properties in the HAZ including strength, hardness, ductility and toughness is inevitable [5]. As a result, there are concerns about the performance of welded high strength steel connections under both static and dynamic applications. Specifically, fatigue performance is frequently a concern since failure very often initiates at the weld toe area which could be affected by welding heat input [6].

Post-weld heat treatment (PWHT) is normally applied to mild steel weldment to remove residual stress, restore deformations during welding or improve the load-carrying capability in the brittle fracture temperature range of service. In fact, the beneficial effects of PWHT are not primarily due to reduction of residual stresses, but rather due to improvements of metallurgical structure by tempering and removal of aging effects [7]. This process is widely accepted as beneficial for mild steel weldment since the microstructure of mild steel, i.e. the mixture of pearlite and proeutectoid ferrite formed at temperature above normal PWHT range, would be hardly altered unless the time of heating is prolonged or higher than usual temperature are employed during the treatment [2]. However, PWHT may introduce unpredictable changes into the microstructure of hardened or high strength steel weldment, which is extremely complicated and normally very sensitive to heat. This is why PWHT is *not*

recommended by the AWS (clause 3.14) [8] for quenched and tempered steel and cold work hardened steel, despite tempering is necessary in manufacturing quenched and tempered steel. Therefore, cautions must be paid when designing the heat treatment solution for high strength steel structures and welded connections.

The main objective of this paper is to investigate the potential effects of PWHT on the reheated, quenched and tempered (RQT) grade S690 high strength steel welded connections. In the first phase of this study, a special welding procedure was designed to manufacture some welding affected coupon specimens. Following the recommendations of PWHT provided by the AWS structural welding code for steel [8], PWHT with different holding temperatures and holding times were conducted. Through the subsequent mechanical property tests, the effects of the PWHT methods were evaluated. The second phase of this study investigated the effect of PWHT on the residual stress level of four Y-shape plate-to-plate (Y-PtP) RQT S690 joints and the tensile behavior of nine T-stub RQT S690 joints. The hole drilling method was employed to measure the residual stress distribution near the weld toe of the Y-shape PtP joints and the tensile performance of the T-stub joints was examined by using a specially designed and fabricated test set-up.

2. PWHT for High Strength Steel

2.1 Material used

The high strength steel studied in this research is a reheated, quenched and tempered structural steel plate in grade S690. The reheated, quenched and tempered technology is essentially a refined quenching and tempering technology. In general, reheated, quenched and tempered steel plates exhibit better homogeneity in through-thickness mechanical properties compared with traditional directly quenched and tempered steel plates. The mechanical

properties of the 8mm and 16mm RQT-S690 plates obtained by standard coupon tensile test are shown in Table 1 and are compared with the corresponding standard EN 10025-6 S690Q/QL [9] and the common S355J2H steel. From Table 1, it can be seen that this material has superior strengths compared to normal strength steels. The actual yield strength of RQT-S690 is more than 180% of the yield strength of S355J2H steel.

2.2 The PWHT process

Generally, the PWHT processes in this study were designed based on the recommendations provided by the AWS with amendments that are probably beneficial for RQT-S690 and suitable for the available laboratory equipment. The common heat treatment temperature for normal strength steels ranges from 600°C to 650°C. However, the allowable maximum heat treatment temperature for quenched and tempered steels is 600°C as specified by the AWS [8] in consideration for the deterioration of mechanical properties after heating and cooling down. In heat treatment for steels, the maximum holding temperature and the holding time at the maximum holding temperature are the two most important factors that would influence the final mechanical properties of the steel under treatment [10]. A reduced temperature with longer holding time may lead to the same heat treatment result of a higher temperature with shorter holding time. Note that even the reduced 600°C holding temperature is not a safe limit for heat treating for RQT-S690 weldment since it is proven that maintaining at 600°C for just 10 minutes would be enough to introduce noticeable changes to the mechanical properties of RQT-S690 base metal [12, 13]. Therefore, in this study, additional reduced temperature cases of PWHT at 570°C and 540°C were designed for RQT-S690. However, in this study heat treatment temperature below 510°C was not employed in order to avoid the 500°C *embrittlement phenomenon* [1, 7].

3. Study Phase I: Effect of PWHT on mechanical properties

3.1 Specimen preparation

Theoretically, the mechanical properties of the materials inside the HAZ can be assessed by direct removal and examination of small samples from the welded joints. However, this method presents many difficulties in practices such as delicate positioning of the HAZ within very narrow zones with high microstructure gradients, uneven residual stresses distribution, etc. Instead, the properties of these zones are often assessed on the basis of experiment on test-samples that undergone simulated thermal treatments representative of those encountered in the HAZ [7].

In this study, the main idea for HAZ property evaluation is to test some specially designed thin coupon specimens that have been affected by welding. The coupon specimen configuration adopted a relatively large cross section with big width and relatively small thickness. To make the material fully affected by welding, a special welding process was designed: Welding was carried out on both sides of a large plate with dimensions of 3000mm×300mm×8 mm, as shown in Fig. 1. Welding was carried out in the central area of the plate along the longitudinal direction. Since the gauge length of the coupon specimen was 100mm, the welding zone was designed to eventually cover the full parallel length of the final coupon specimens which was 120mm long, as shown in Fig. 2. Since the plate thickness is relatively small, special caution was also paid to the welding sequence in order to control the deformation associated with uneven heating and cooling. Every time when two runs were finished on one side of the plate, the welding moved to the other side (Fig. 1). After the welding was completed, the welding affected plate was cut, grinded (Fig. 3) and eventually fabricated into standard coupon specimens (Fig. 4). It should be noted that all subsequent cutting and grinding processes following the welding are accompanied with water cooling to avoid additional heat input into the coupons.

3.2 The PWHT process

Table 2 summarizes the PWHT schedules applied for the RQT-S690 welding affected coupon specimens. Three different holding temperatures (600°C, 570°C and 540°C) and two holding times (full and half) recommended for the corresponding holding temperatures are tested for the specimens.

To fulfill the heat treatment task, a laboratory heating furnace with a maximum heating capacity of 1200°C and robust refractory bricks inside was employed to simulate the thermal cycles of PWHT. The internal dimensions (width × depth × height) of the oven were 500×500×700 mm. As the specimens are very small compared with the oven and the robust refractory bricks on the inner side of the furnace frame ensured the insulation of heat, high heating and cooling speeds as well as homogeneous atmosphere in the oven were guaranteed. In order to release the thermal expansion or contraction during the heat treatment, the specimens were simply supported in the oven by two ceramic bars, as shown in Fig. 5. During heat treatment, thermocouple was employed to monitor and record the temperature-time history (thermal cycles) that the specimens were subjected to. The thermal cycles of for the PWHT-600°C, 20min, the PWHT-570°C, 38min and the PWHT-540°C, 77min cases are shown in Fig. 6. It can be seen from Fig. 6 that relatively fast heating, stable maintenance at the maximum temperature and slow cooling above 300°C were achieved during all cases.

3.3 Tensile test after PWHT

After the PWHT, tensile tests were carried out for the heat treated specimens. The loading rate was set as 1mm/min until fracture took place and data points were captured at a frequency of 1 Hz. During the tensile test, both strain gauge and extensometer were used to monitor and record the deformation.

The test results in terms of stress-strain curves for different cases are shown in Fig. 7, and the nominal yield strengths (the 0.2% strain offset strengths), the tensile strengths, the tensile ratios as well as the strains at fracture obtained are summarized in Table 3. Note that in Fig. 7 and Table 3, data obtained from the original plate (RQT-S690) and the as-welded coupon without PWHT (AW-HAZ) are also plotted and given. As shown in Fig. 7 and Table 3, PWHT improved the deformation capacity at the expense of strength, which exactly reversed the work hardening process. Judging by the improvement in ductility and lost in strength, the 570°C, 19min PWHT was the best treatment solution. In this case, the ductility was improved from 11.6% to 19.8% while the yield and tensile strengths were only compensated for 1.7% and 0.7% respectively when compared with the as-welded specimens (AW-HAZ in Table 3). From Fig. 7, it can be seen that the 570°C, 19min specimen clearly showed a longer hardening stage. The tensile strength of the 570°C, 19min specimen was not significantly less than that of the AW-HAZ but achieved a much higher strain level. Similar changes happened to the 570°C, 38min specimen and the 540°C, 38min specimen, but the strength losses in these two cases are more than that of the 570°C, 19min specimen. It should be noted that both the strengths and ductility of the 570°C, 38min specimen were less than those of the 570°C, 19min specimen. In fact, they were even slightly lower than those of the 540°C, 38min specimen (Fig. 7). These are possibly due to overheating or over treatment. The more obvious over treatment cases are the 600°C, 20min PWHT and the 540°C, 77min PWHT. The 600°C, 20min PWHT showed the ability of improving ductility to a level comparable to the 570°C, 38min PWHT and the 540°C, 38min PWHT, but it softened the material significantly. Not only the strengths were decreased a lot, but also the tensile strength appeared at smaller strain. As for the 570°C, 77min specimen, the ductility was improved for only 1.3%, but the yield strength and tensile strength dropped 21.8MPa and 56.4MPa, respectively (Table 3, row 8). It should be mentioned that besides the discussed 6 specimens (Table 3 and Fig. 7), many other

specimens are tested to investigate the influence of important test variables such as thickness, holding temperature, holding time and cooling rate. The results of these specimens are not shown in this paper, because these specimens are either not fully affected by the welding process (too thick) or are subjected to PWHT methods different from those in Phase II of this study.

4. Study Phase II: PWHT for high strength steel Y-shape plate-to-plate and T-stub joints

4.1 Specimens preparation

Nine T-stub joints as well as four 45° Y-shape Plate-to-Plate (Y-PtP) joints were fabricated. The purpose of the T-stub joints was to investigate the effect of PWHT on the tensile behavior while the Y-PtP joints were used to study the effect of PWHT on the residual stress distribution. The reason for not using T-stub joints in the residual stress test is that their braces severely limited the space available and blocked the access of the drilling machine that is employed to measure residual stress [3]. Each specimen is fabricated by joining two identical steel plates with dimensions of 440×150× t mm, where t is the thickness of the plates. These joints are designed as *complete penetration butt weld joint* according to the AWS structural steel welding code [8]. Three bolt holes were drilled at each side of the chord plate in order to fix the specimens to the test rig. The distance between two rows of bolt holes (center to center) is 290 mm. The configuration of the T-stub joints is shown in Fig. 8 while the Y-PtP joints set up is exactly the same but with a different brace-chord angle of 45°. Shielded Metal Arc Welding (SMAW) was employed to finish the welding. Compared to the other common welding methods, SMAW is more “friendly” to martensite-based high strength steels such as RQT S690 steel due to its low heat input [13] which produce less effect on the HAZ.

Based on the insights obtained in the Phase I of the current study for the effect of PWHT on the mechanical properties of the HAZ, PWHT at a holding temperature of 570°C was chosen. The PWHT scheme employed for all the joints tested are shown in Table 4. From Table 4, it can be seen that both full holding time (as recommended by the AWS) and half holding time were adopted for the RQT-S690 T-stub joints while half holding time was adopted for the Y-PtP joints. For each specimen, one as-welded (AW) specimen was also tested to serve as a control specimen. It should be noted that although the experimental program of Phase II is designed based on the knowledge obtained from Phase I, the mechanical properties of the HAZ of the T-stub joints may be different from those of the welding affected coupon specimens due to different thermal cycles and geometries. Therefore, the effect of the PWHT on the T-stub joints may also be different from the coupon specimens.

4.2 Test program

4.2.1 Residual stress measurement of the Y-PtP joints

Since it is well known that the residual stress level in quenched and tempered steels, especially after welding, are usually high, there are concerns that residual stress may affect the performance of welded high strength steel connections. Lee et al. [3] carried out an experimental investigation of the residual stress distribution near the weld toe of RQT-S690 Y-PtP joints with similar geometrical parameters to those tested in this study. Test results showed that tensile residual stress could be as high as 1/3 of the yield strength near the weld toe (5mm away from the weld toe), and the level of residual stress increases with thickness.

In this study, the residual stress distributions of the AW and PWHT Y-PtP joints were investigated again by the hole drilling method. The hole drilling method is a type of localized measurement method that measures the amount of residual stresses within the boundaries of the drilled hole [14]. The concept is quite general, but this test method is only applicable in those cases where the stresses do not vary significantly with depth and do not exceed one half

1 of the yield strength. Although the hole-drilling method was known to be only a semi-
2 destructive method, the drilled holes easily cause serious stress concentrations and are
3 artificial defects that may initiate crack and fracture. Considering the HAZ usually has the
4 highest level of residual stresses caused by welding and is very often just located in the plastic
5 hinge zone during the final failure of the joint, it is expected that the hole drilling method will
6 inevitably affect the failure strength of the joint. Hence, no tensile test was conducted on the
7 Y-PtP joints after their residual stress were measured by the hole drilling method.

8 Fig. 9a shows a specimen with strain gauge rosettes attached while Fig. 9b shows the
9 arrangement of the residual stress measurement locations. It can be seen from Fig. 9b that
10 strain gauge rosettes are arranged in three rows with distances of 5mm, 15mm and 25mm
11 away from the weld toe. The distances between the strain gauge rosettes and the chord edge or
12 the adjacent two rosettes is 37.5mm (one quarter of the chord width). During the test, a hole
13 with certain depth is drilled on the special strain gauge rosette in several steps depending on
14 the calculation method and the precision requirement. In this study, the 1.6mm diameter
15 tungsten carbide cutter was employed for drilling so that the hole dimension meets the
16 1.77mm diameter criterion [14]. The nominal gauge size (D) of the used strain gauge rosette
17 was 5mm. To complete drilling for one hole with depth of 0.4D, eight drilling steps with
18 depth of 0.05D were taken. The released strains at each step were then recorded for further
19 residual stress calculation using the formulas provided in ASTM E837-08 [14].

20 4.2.2 Tensile Test of the T-stub joints

21 Tensile tests for the T-stub joints were carried out in a servo-hydraulic universal test machine
22 that has a maximum loading capacity of 2000kN. To fix the specimen into the test machine, a
23 specially designed “inverted” support joints made of S355 steel plates with thickness of
24 50mm were fabricated. The configurations of the support joints are the same as those of the
25 test joints (Fig. 8). The specimens are fixed into the support joints by six M24 high strength

hexagon bolts of grade 10.9HR. The full testing set-up is shown in Fig. 10. To ensure the T-stub joints to be loaded vertically, a spirit level was used to adjust the position of the specimens during mounting. To capture the load-displacement relationship of the specimens precisely, LVDT was employed to record the real-time displacement at the brace end. Since it would be easier to control the testing time, displacement control instead of force control was used during the testing. The loading rate was set as 1mm/min for all time so that quasi-static response could be obtained.

4.3 Test results

4.3.1 Residual stress distribution near the weld toe

Tables 5 and 6 present the residual stress distribution perpendicular to the weld line (S11 direction) of the 45° Y-PtP 12mm specimen and the 45° Y-PtP 16mm specimen before and after the PWHT, respectively. The residual stress distributions were roughly symmetrical about the center S11 axis, where the constraint from the adjacent material is the highest. By comparing the distributions of the AW specimens and the distribution after PWHT, it is clear that PWHT is capable of reducing the level of residual stress. First, the maximum residual stress in the 12mm specimen dropped from 236MPa to 60MPa, while that in the 16mm specimen dropped from 255MPa to 73MPa. In fact, the changes are more than just reducing the maximum residual stress value to 25% of the original values: the PWHT actually lowered the residual stress level from quenched and tempered steel to a level similar to hot-rolled section with similar thickness [15]. On this basis, it is possible that the current residual stress related design approaches and safety evaluation processes for hot-formed structures could be applicable for RQT-S690 structures if a *proper* PWHT is carried out. Secondly, the stress distribution within the specimens becomes more uniform after PWHT. However, it should be noted that the hole drilling method employed was only able to measure residual stress within

the drilled *2mm deep* hole. Hence, the values shown in Tables 5 and 6 are just the distribution of the mean surface residual stress. Originally, the measured residual stresses on the AW joint were all tensile stresses. To self-balance these tensile stresses, there must be compressive stresses in the core of the specimens. After the PWHT, the appearance of compressive stresses on the surface indicated that the original surface tensile stresses were significantly released or redistributed. To maintain the self-balance, the originally high compressive residual stresses in the core must be redistributed as well. As a result, one can easily infer that the stress distribution must become more uniform in the thickness direction of the joint after the PWHT.

4.3.2 Tensile behavior of the T-Stub Joints

4.3.2.1 General descriptions

Figs. 11 to 13 show the load-displacement curves of the 8mm, 12mm and 16mm RQT-S690 T-stub joints, respectively. In general, three stages in the load-displacement curves can be distinguished: (1) the elastic stage, (2) plastic hinge development stage and (3) the failure stage. In the elastic stage, stiffness and the elastic modulus govern the behaviors of the joints until general yielding takes place in the large deformation zones. When the specimens are further loaded, plastic deformation would appear and four obvious plastic hinges could be seen, as shown in Fig. 14. Two of the plastic hinges would appear near the weld toe, and the other two would be near the bolt area. In this stage, the deformation grows wildly but the carried load increases slowly. If the loads are further increased, due to large deformation of the joint, stronger hardening effects than those in the plastic hinge development stage occur, final failure would soon happen in the forms of either weld toe through thickness fracture or bolt hole necking failure. It should be noted that the resistances of the joints including load carrying capacity (plastic resistance and maximum resistance) and deformation ability (ductility) are fully dependent on the resistances and ductility of the plastic hinges.

4.3.2.2 Load resistance and ductility

From Figs. 11 to 13, it can be observed that PWHT was able to improve the global ductility compared to the AW specimens. Although the PWHT specimens showed lower resistance at the same displacement level, the maximum strength of the PWHT specimens may exceed the AW specimens because of the benefits from hardening effect which was due to better deformation ability. In particular, the effects of 570°C, half holding time PWHT (Table 4, column 5) seem to be quite inspiring. The loss of strengths is reasonably small compared to the remarkable improvement on the maximum resistance and ductility. However, similar to the findings observed in Fig. 7, 570°C, full holding time PWHT seemed to be too strong for the RQT-S690 specimens. Although the ductility was improved, the loss of strength is also rather significant. Another phenomenon showing the beneficial effect of PWHT on the tensile performance is that the failure modes of the specimens were slightly altered after the PWHT. Figs. 15a and 15b respectively show the deformed shape of the plastic hinges at the bolt hole area for the AW joint and the 570°C half holding time joint when final failure took place. It can be seen that necking existed in Fig. 15b but not in Fig. 15a. This indicates that the deformation ability of the PWHT specimen was superior to that of the AW specimen.

In EC3, three failure modes are specified for typical T-stub joints namely, mode 1: complete yielding of the flange, mode 2: bolt failure with yielding of the flange and mode 3: bolt failure [16]. In this study, all the specimens are failed in mode 1. The EN 1993-1-8 [16] gives two methods based on yield line analysis to predict the load carrying capacity of the T-stub joints failed in this mode. The design plastic resistance of the simplified method can be expressed as:

$$F = \frac{4M_{pl,1,Rd}}{m} \quad (\text{Eqn. 1})$$

In Eqn. (1), $M_{pl,1,Rd} = l_{eff}(\frac{t_f}{2})^2 f_y$ is the design moment resistance of the section. m and t_f are geometrical parameters of the T-stub joints, as shown in Fig. 16. l_{eff} , the total effective length of an equivalent T-stub, in this case is the width of the T-stub joint. f_y is the nominal yield

1 **strength of the steel plate.** Based on the load-displacement curves (Figs. 11 to 13), two
2 characteristic strengths including the actual plastic resistance achieved (see definition in Fig.
3 17) and the actual maximum resistance (i.e. highest resistance shown in Figs. 11 to 13) can be
4 defined. In addition, two characteristic ductility indicators including the crack initiation
5 displacement and final failure displacement can be obtained from the tests. The results
6 obtained for the AW joints and those with PWHT are summarized in Table 7 together with
7 design plastic resistance based on EC3 Eqn. 1. Furthermore, data in Table 7 are analyzed by
8 calculating the percentage differences between the AW joints and the PWHT joints in the
9 form of $PWHT/AW \times 100\%$ and the results are plotted in Figs. 18 and 19.

10 It can be seen from Table 7, Figs. 18 and 19 that the actual plastic resistances of the tested
11 specimens are very close to the design plastic resistances obtained by using Eqn. 1 and only
12 the resistances of the 8mm specimens are lower than the prediction. The actual plastic
13 resistances of the PWHT specimens are all lower than the AW, and the difference varies from
14 1.1% (PWHT-570°C-29min) to 6.1% (PWHT-570°C-38min). For the actual maximum
15 resistance, the 570°C, half holding time PWHT improved the maximum resistance by 5.9%
16 (8mm) to 14.5% (12mm). However, the effect of 570°C, full holding time PWHT on the
17 maximum resistance was not always beneficial. After PWHT, the actual maximum resistance
18 of the 8mm specimen increased by 9.3% but those of the 12mm and 16mm specimens
19 decreased by 2.7% and 8.1%, respectively. On the other hand, all the treated specimens
20 showed improved ductility compared to the AW specimens. As far as crack initiation
21 displacement is concerned, PWHT at half holding time improved the ductility of the 12mm
22 and 16mm specimens by 14.1% and 9.2%, respectively; while PWHT at full holding time
23 improved the ductility of 12mm and 16mm specimens by 15.1% and 9.1%, respectively.
24 Similar changes can be observed on the final failure displacement, despite that PWHT at full
25 treatment time showed better improvement on the 8mm specimen.

5. Conclusions

Post-weld heat treatment (PWHT) for the reheated, quenched and tempered (RQT) grade S690 high strength steel welded connections was investigated and tested in two phases study. Phase I of this study investigated the effect of PWHT on the mechanical properties of welding affected coupon specimens. A special welding procedure was conducted to obtain the welding affected coupon specimens. Through the mechanical property test, it was found that welding may cause serious deterioration in both strength and ductility. However, appropriate PWHT was able to improve the ductility of the welding affected specimens at the expense of strength. For the specimens tested in this study, the best PWHT for RQT-S690 was found to be treatment at 570°C for half of the recommended holding time by the AWS. Phase II of this study investigated the effect of PWHT on the residual stress level at the weld toe of four Y shape plate-to-plate (Y-PtP) joints and the tensile behavior of nine T-stub joints. The hold drilling tests revealed that PWHT was able to reduce the residual stress level significantly and even out the residual stress distribution near the weld toe. PWHT at 570°C for half holding time again turned out to be effective in improving both the ductility and the maximum resistance of the joints tested, and the loss of plastic resistance was at negligible level. However, it was also found that 570°C, full holding time PWHT seemed to over treat the specimens. Although the ductility could still be increased, the reduction of load carrying capacity was severe.

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Table 1. Mechanical properties of RQT-S690 Steel

	f_y (MPa)	f_u (MPa)	E (GPa)	Elongation (%)
RQT-S690 (8mm)	769.0	849.8	206.5	14.7
RQT-S690 (16mm)	745.2.0	837.8	208.9	14.5
EN 10025-6 S690Q/QL (3mm≤t≤50mm)	690	770-940	-	14
S355J2H	410	535	208.4	30.2

Table 2. Summary of the PWHT schedule for the welding affected coupons

	Holding Temperature (°C)	Full Holding Time (min)	Half Holding Time (min)
PWHT-600	600	20	N.A.
PWHT-570	570	38	19
PWHT-540	540	77	38

Table 3. Summary of the mechanical properties of the welding affected specimens after PWHT

	0.2% strain offset strength (MPa)	Tensile strength (MPa)	Tensile ratio	Strain at fracture (%)
RQT-S690 (8mm)	769.0	849.8	1.11	14.7
AW-HAZ	450.3	594.4	1.32	11.6
PWHT-600-20min	402.9	508.4	1.26	15.9
PWHT-570-19min	442.5	590.3	1.33	19.8
PWHT-570-38min	440.8	575.1	1.30	15.5
PWHT-540-38min	448.1	567.5	1.27	16.2
PWHT-540-77min	428.5	538.0	1.26	12.9

Noted: The tensile ratio is calculated as Tensile strength/0.2% strain offset strength

RQT-S690 refers to the parent steel before welding.

AW-HAZ refers to the aw-welded specimens without PWHT

Table 4. PWHT schedule for the T-Stub and the Y-PtP joints

thickness	Control Specimen	Holding Time (PWHT at 570°C)	
T-stub Joints	8	AW	38
	12	AW	58
	16	AW	77
Y-PtP Joints	12	AW	-
	16	AW	-

Table 5. Residual stress distribution (MPa) of Y-PtP 12mm joint in S11 direction

Positions		AW			PWHT		
		S33 direction			S33 direction		
		37.5mm	75.0mm	112.5mm	37.5mm	75.0mm	112.5mm
S11 direction	5mm	68	236	76	-10	60	-3
	10mm	56	161	55	7	57	12
	15mm	12	28	41	16	40	-21

Unit: MPa, tensile stress is positive

Table 6. Residual stress distribution (MPa) of 45°Y-PtP 16mm joint in S11 direction

Positions		AW			PWHT		
		S33 direction			S33 direction		
		37.5mm	75.0mm	112.5mm	37.5mm	75.0mm	112.5mm
S11 direction	5mm	-22	285	42	-16	-2	7
	10mm	-35	213	21	-1	73	-39
	15mm	-10	80	1	-13	-20	14

Unit: MPa, tensile stress is positive

Table 7. Summary of the tensile test results of the T-stub joints

Specimens	Design plastic resistance (KN) EC3, Eqn. 1	Actual Plastic resistance (KN) (Fig. 17)	Maximum resistance (KN) (Figs. 11 to 13)	Crack initiation displacement (mm)	Final failure displacement (mm)
8 mm	AW	44.2	276.7	N.A.	34.2
	PWHT-570°C-19min	42.9	293.1	N.A.	37.1
	PWHT-570°C - 38min	41.5	302.3	N.A.	40.5
12 mm	AW	126.3	504.7	34.8	37.0
	PWHT-570°C - 29min	122.4	577.8	39.7	41.2
	PWHT-570°C - 58min	120.3	491.2	38.0	38.8
16 mm	AW	217.8	621.3	36.4	40.2
	PWHT-570°C -38min	215.3	665.9	41.9	45.4
	PWHT-570°C -77min	212.5	571.2	39.7	41.9

Fig. 1. Welding procedure for the fabrication of welding affected coupon specimens

Fig. 2. Welding affected zone on the final coupon specimens

Fig. 3. Grinding machine with water cooling system

Fig. 4. Final welding affected coupon specimens

Fig. 5. The furnace employed for the heat treatments

Fig. 6. Typical thermal cycles of the PWHT

Fig. 7. Stress-strain curves of the welding affected coupon specimens after PWHT

Fig. 8. Configuration of the T-stub joints

(a) Test specimen with strain gauge rosette

(b) Test locations

Fig. 9. Hole drilling test to measure the residual stresses distribution of Y-PtP joints

Fig. 10. T-stub joint test setup

Fig. 11. Load-displacement curves of the 8mm T-stub joints

Fig. 12. Load-displacement curves of 12mm T-stub joints

Fig. 13. Load-displacement curves of 16mm T-stub joints

Fig. 14. Plastic hinge formed in T-stub joint test

(a) AW specimen (elevation view)

(b) PWHT-570-19min specimen (elevation view)

Fig. 15. Plastic hinges at the bolt hole area of the 16mm joints under AW and PWHT-570-19min conditions

Fig. 16. Analytical model of a deformed T-stub joint

Fig. 17. Definition of design plastic resistance

Fig. 18. Effect of 570°C PWHT at half holding time

Fig. 19. Effect of 570°C PWHT at full holding time