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<td><strong>Author(s)</strong></td>
<td>Zhao, Ming Shan; Lee, C. K.; Chiew, S. P.</td>
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Title: Tensile Behavior of High Performance Structural Steel T-stub Joints

Article Type: Research Paper

Keywords: Tensile Behavior; High Performance Structural Steel; T-stub Joints; Design Resistance; Stiffness

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Abstract: In this study, experiments were conducted to investigate the tensile behavior of ten T-stub joints made of different types of high performance structural steel including the Reheated, Quenched and Tempered (RQT) grade S690 high strength steel, the Thermal-Mechanical Controlled Processed (TMCP) grade S385 and S440 structural steels. The results were further validated against the analytical yield line method and the design resistance equations provided by the EC3. It is found that the behavior of the T-stub joints made of S385 and S440 steels reasonably agreed with analytical approach and the predictions by the EC3. However, although the S690 specimens showed higher design resistance than the S385 and S440 specimens with the same thickness, the results were significantly lower than both the predictions by the analytical approach and the EC3. In addition, the ductility of the S690 specimens is also found to be significantly lower than that of the S440 and S385 specimens and failed in more brittle failure modes.

Response to Reviewers: For the respond to reviewers' comments, please kindly refer to the attached reply summary.
Dear Prof. Bjorhovde,

Paper Ref. No.: JCSR-D-15-00491

Tensile Behavior of High Performance Structural Steel T-stub Joints

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

Thanks for your email of 10 March 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

- Stiffness, design and ultimate resistances of RQT and TMCP joints are studied
- Yield line model and EC3 safely predict the design resistance of TMCP joints
- Design resistances of RQT-S690 joints are lower than yield line predictions
- Strength reduction of RQT joints may be caused by heat inputs during welding
Replies to comments from Reviewer #1

General:

The paper reports an experimental investigation on large deformation behaviour of welded T-sections made of high strength steel plates with different delivery conditions. A total of ten welded T-sections were tested under large pull-out forces applied to the webs of the T-sections while the flanges of the T-sections are bolted onto supports. Both the pull-out forces of the T-sections and the corresponding deformations at different stages of deformations are measured. Design rules according to Structural Eurocodes and other sources are also employed to predict the pull-out resistances of the T-sections for comparison.

The paper is recommended to be published after suitable revisions according to the following recommendations:

Specifics:

1. In Section 1 Introduction, both the objectives and the scope of work of the research study should be clearly identified. The methodology should be clearly explained and justified.

Authors’ reply: Agreed.

Amendments made: Amendments are made to the Section 1 Introduction accordingly. The objective, scope and methodology are identified and emphasized.

2. In Section 2, the title "The experimental program" should be replaced with "Experimental Investigation". A detailed test programme in tabulated format should be provided to list out various key parameters of the ten T-sections tested.

Authors’ reply: Agreed on the title change. The ten T-stub joints are of the same configuration as shown in Fig. 2. The differences in the ten specimens are only in grade and thickness. Three grades of steels, namely the TMCP steel plates in grades S385 (thickness 16mm) and S440 (thickness 22mm) and the RQT grade S690 HSS (thicknesses 8mm, 12mm and 16mm), are examined. For each of these 5 combinations of steel grades and plate thickness, two joints were fabricated and tested. Since the “key parameters” are straightforwardly identified, no further table showing the detailed test programme is provided.

Amendments made: Title is changed accordingly. Further explanation is made in Section 2.2 to clearly identify the test programme and the key parameters of the ten T-stub specimens.
3. In Section 2.2 Specimen fabrication, Figure 2 should be revised to illustrate geometrical dimensions of the T-sections and details of the bolt configurations including bolt spacing, and edge and end distances. Have the bolt forces been measured during tests?

Authors’ reply: Agreed for the changes of Figure 2. The bolt forces are not measured during tests. After the tests are done, the bolts were examined and no obvious plastic deformation was observed. Hence, it is believed that the bolts were working in elastic stage.

Amendments made: Fig. 2 has been updated. The dimensions of the T-sections and details of the bolt configurations are included.

4. (i) In Section 3 Test results, Tables 2 and 3 should be re-formatted to precisely list out the measured resistances and the corresponding deformations of the T-sections.

(ii) In Figure 4, define the term “Displacement”, and show how the quantity is measured in Figure 3.

(iii) In Figures 6 and 8, the term "Design plastic resistance" should be referred as "First yield resistance" as it is evident that plastic hinges have not been formed yet!

Authors’ reply: (i) Table 2 shows the stiffness of the joint at the elastic stage. Table 3 lists the design plastic resistance of the T-stub joints based on the yield line analysis (see definition in Figs. 6 and 8). These two values are obtained by analyzing the load-displacement curves and therefore do not have a corresponding deformations.

(ii) Displacement in Fig. 4 is the vertical displacement at the brace end which is measured by LVDT (as described in Section 2.3).

(iii) Agreed and the terms changed.

Amendments made: (i) No amendments is made. (ii) Fig. 3 is updated with indication of displacement load direction. (iii) The term “Design plastic resistance” is replaced by “First yield resistance” in Figs. 6 and 8, as well as corresponding descriptions in the context.

5. In Section 3.2.1 Stiffness, please explain the significance of the "stiffness" of the T-sections as it is not obvious to the reviewer the reason(s) of working with stiffness at all. How is the quantity used?

Authors’ reply: Firstly, the stiffness govern the behaviors of the joints until yielding take place, regardless of the grade of steel used. Secondly, comparable stiffness shown by the different specimens implies that the test results are consistent and repeatable.
Thirdly, the stiffness values obtained in this section are further used in the analytical approach to calculate the value of $K$ (used Eqn. 18), as stated in Section 4.

**Amendments made:** No amendment is made for this comment.

6. (i) In Section 3.3 Plastic hinge and failure stages, Table 5 should be revised to list out various modes of failure at different stages of deformation. The present table fails to present development of failure modes along deformations of the test specimens.

(ii) What are $S1$ and $S2$?

(iii) In general, measured (rather than nominal) yield strengths of the steel plates should be used in back analysis of design methods, and these resistances should be presented systematically in Table 6, according to different modes of failure. Large tensile forces induced in the flanges of the T-sections at large deformations are not mentioned at all. Please clarify.

**Authors’ reply:** (i) The failure modes of all the specimens happen in the final failure stage, which is long after the plastic hinge was fully developed. The discussion of deformation at this state is hardly meaningful.

(ii) $S1$ and $S2$ correspond to Specimen 1 and Specimen 2, as tested for each type of joint.

(iii) Agreed. The “Test” and “YL Model” used the actual yield strengths of the steel plates, while the Eqns. 3 and 4 use nominal yield strengths which follows EC3. The purpose here is to compare the design resistance obtained by Test, YL Model and EC3 equations. The design plastic resistance refers to the “First yield resistance”, which is suggested by Reviewer #2. Therefore, large tensile forces have not been induced in the flanges yet.

**Amendments made:** The definition of $S1$ and $S2$ are added below Table 5.

7. (i) In general, Figures 9, 11 and 12 are not necessary, and they should be removed from the manuscript.

(ii) In Figure 15, the caption "Ductile bolt hole are necking failure" should be replaced with "Net section failure under tension".

**Authors’ reply:** (i) Fig. 9 shows the stiffness of the joints during the elastic stage. The importance of Fig. 9 (for the calculation of $K$ in Eqn. 18) is explained in the reply to Question #5. Fig. 11 compares the design plastic resistance obtained by test and EC3 equations. It can be clearly seen from Fig. 11 that the test values of RQT-S690 are generally between the predictions by Eqn. 3 and Eqn. 4, while the test values of TMCP are higher than the respective equation values. Fig. 12 presents the stiffness of the joints during the plastic hinge stage. RQT-S690 specimens show higher stiffness than the TMCP specimens, which may be the result of stronger strain hardening effect. This is one of the main differences between RQT and TMCP material.

(ii) Agreed. The caption “Net section failure under tension” is more appropriate.
**Amendments made**: Figs. 9, 11 and 12 are kept. The caption of Fig. 15 is changed to “Ductile net section failure under tension”. The corresponding description in the context is also amended.

8. Various parts of Sections 3 and 4 should be significantly re-written in order to present the test results and the comparison with design resistances in a professional manner.

**Authors’ reply**: The authors have revised various parts of Sections 3 and 4 carefully to improve the presentation of the results and comparison and to clear all typo and grammatical errors.

**Amendments made**: Various parts are amended. Please refer to the manuscript.

**Replies to comments from Reviewer #4**

My congratulation to nice experiments and models. I recommend publication “as is”.

**Authors’ reply**: The authors thank the reviewer’s appreciation sincerely.

**Amendments made**: No amendments are made.
Tensile Behavior of High Performance Structural Steel T-stub Joints

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Abstract

In this study, experiments were conducted to investigate the tensile behavior of ten T-stub joints made of different types of high performance structural steel including the Reheated, Quenched and Tempered (RQT) grade S690 high strength steel, the Thermal-Mechanical Controlled Processed (TMCP) grade S385 and S440 structural steels. The results were further validated against the analytical yield line method and the design resistance equations provided by the EC3. It is found that the behavior of the T-stub joints made of S385 and S440 steels reasonably agreed with analytical approach and the predictions by the EC3. However, although the S690 specimens showed higher design resistance than the S385 and S440 specimens with the same thickness, the results were significantly lower than both the predictions by the analytical approach and the EC3. In addition, the ductility of the S690 specimens is also found to be significantly lower than that of the S440 and S385 specimens and failed in more brittle failure modes.
Keywords: Tensile Behavior; High Performance Structural Steel; T-stub Joints; Design Resistance; Stiffness

1. Introduction

Structural steel is one of the most popular materials employed in civil engineering construction due to its high strength, stiffness, toughness and ductile properties. With the continuous development of new design ideas and manufacturing technologies, steel as a material for structural application has undergone significant changes. In the 1900s, most primary structural steel only had nominal yield strengths of about 220MPa, which is equivalent to today’s “mild steel”. The once so called “high strength” steel S355 is now a widely used structural material. In fact, steels with yield strength up to 460MPa have been commonly specified for applications in many structural design codes [1, 2]. Furthermore, due to its higher strength to weight ratio and potential to offer a lower total material cost and aesthetic advantages, the interests of using high strength steel (HSS) with minimum yield strength greater than 460MPa in structural application have been increasing in the last decade.

In EC3, a structural steel can be classified as HSS given that its yield strength $f_y$ satisfies $460\text{MPa}<f_y\leq700\text{MPa}$, its ultimate strength ($f_u$) to $f_y$ ratio satisfies $f_u/f_y>1.05$, the elongation at failure at least than 10% and its yield ($\varepsilon_y$) and ultimate strain ($\varepsilon_u$) satisfy $\varepsilon_u\geq15\varepsilon_y$, while the rest mechanical properties remain the same as normal strength steel (NSS) [1]. For many types of HSS such as the RQT S690 steel, the actual yield strength can be easily double that of grade S355 NSS. However, strength is not the only aspect that HSS differs from the NSS. One major issue prevent the popular use of HSS is that while the quenching and tempering process improves the strength, it often reduces its ductility through the complicated heat treatment process. Many researchers have demonstrated that it is not possible for quenched and tempered HSS steels to achieve good deformation capacity [3-5] and their mechanical
properties are more susceptible to heat [6, 7] than mild steels, as inherited from the heat-
treatment hardened microstructures [8]. Researchers also found that the mechanical
properties of HSS after exposure to heat (after heated to high temperatures and cooled down)
may be deteriorated significantly [9, 10]. As a result, there are concerns about the
performance of welded HSS connections especially when welding process is involved.

The main objective of this paper is to investigate the tensile performance of welded T-stub
joints that made of three different grades of relatively new structural steels, namely the RQT
grade S690 steel and the TMCP grade S385 and the TMCP grade S440 steel by both
experimental and analytical methods. In the experimental study phase, ten specimens with the
same configuration but fabricated by using different materials and thicknesses are tested until
failure. Both the load-displacement curves and failure modes of the tested specimens are
presented. Specifically, the elastic stage stiffness, plastic resistance and plastic stage behavior
are analyzed. In the analytical study phase, an analytical approach based on the yield line
model [11-13] is developed to predict the load-displacement relationships of these joints at
small deformation stage. By comparing the test results, the yield line model results and the
design equations given by the Eurocodes EN 1993-1-8 [14], the performance of these joints
are evaluated.

2. The experimental investigation

2.1 Materials

Three grades of steels, namely the TMCP steel plates in grades S385 (thickness 16mm) and
S440 (thickness 22mm) and the RQT grade S690 HSS (thicknesses 8mm, 12mm and
16mm), are examined in this study. It should be mentioned that both the TMCP and the RQT
steels are “emerging” types of materials for structural application when comparing with the
commonly used NSS of grade S355 steels or grades S235 and S275 mild steels.
The TMCP is an advanced thermo-mechanical process to produce low carbon high performance plate steels. The concept of TMCP combines controlled hot rolling with accelerated cooling to control the microstructure of the materials [15]. The microstructure provides the ‘fingerprints’ of a steel product that determines its properties. As a result, TMCP enables the production of as-rolled steels with final properties that are tailored to the requirements and specifications of a particular application [16]. The goal of the TMCP is to produce cost-efficient steel strips and plates with properties required for a specific application.

In addition to strength, the hardness and toughness, weldability and corrosion resistance of the steel are usually the targeted material features of the TMCP. The TMCP grade S385 steel (TMCP-S385) tested in this study has a minimum yield strength of 385MPa and a tensile strength between 550MPa and 670MPa, while the TMCP grade S440 steel (TMCP-S440) has a minimum yield strength of 440MPa and a tensile strength between 590MPa and 740MPa.

The RQT is essentially a refined quenching and tempering technology. In general, RQT steel plates exhibit better homogeneity in through-thickness mechanical properties compared with traditional directly quenched and tempered steel plates. The RQT grade S690 steel (RQT-S690) studied in this paper have a nominal yield strength of 690MPa, a tensile strength from 790MPa to 930MPa and an elongation capacity around 15%. The RQT-S690 plates used in this study comply with the EN 10025-6 grade S690 specification [17].

The stress-strain curves and the mechanical properties of the steel plates obtained by standard coupon tensile test are shown in Fig. 1 and Table 1, respectively. Table 1 also compares the materials properties of the TMCP and RQT plates with the corresponding standards of EN 10025-4 [18] and EN 10025-6 [17], respectively. From Table 1, two distinct features of RQT-S690 steel can be seen. First, this material has superior strengths compared to traditional steels. The actual yield strength of RQT-S690 is twice the nominal yield strength of S355. Second, RQT-S690 steel is relatively brittle compared to traditional NSS and the two TMCP
steels tested in this study. For TMCP steels, it can also be seen from Table 1 that the TMCP-S385 steel literally fulfilled the mechanical property specifications of S420M/ML steel and the TMCP-S440 steel fulfilled those of S460M/ML steel.

2.2 Specimen fabrication

Five types of T-joints were fabricated in this study. They were of the same configuration but fabricated by using different materials and plate thicknesses: TMCP-S385 (16mm), TMCP-S440 (22mm) and RQT-S690 (8mm, 12mm and 16mm). For each type of T-joint, two same specimens were fabricated and tested so a total of ten tests were conducted. 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. The joints are designed as complete penetration butt weld joint according to the AWS structural steel welding code [19]. 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 joints is shown in Fig. 2 and Shielded Metal Arc Welding (SMAW) was employed. Compared to the other common welding methods, SMAW is more “friendly” to martensite-based HSS like RQT S690 steel due to its low heat input [20] which produce less effect on the Heat Affected Zone (HAZ).

2.3 Test set-up and testing procedure

Tensile tests for the T-stub joints were carried out in a servo-hydraulic universal test machine that has a maximum loading capacity of 2000kN. To fix the specimen into the test machine, “inverted” support joints made of S355 steel plates with thickness of 50mm were fabricated. The configurations of the support joints are the same as those of the test joints (Fig. 2). 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. 3. To ensure the T-stub 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.

3. Test results

3.1 General descriptions

Figs. 4 and 5 present the test results in terms of the load-displacement curves of the TMCP (S385-16mm, TMCP-S440-22mm) and RQT steel (8mm, 12mm and 16mm) T-stub joints, respectively. Despite that the specimens may fail in different modes and at different loadings, these curves are of the same pattern. In general, three stages in the load-displacement curves can be distinguished: (1) the elastic stage, (2) plastic hinge stage and (3) the failure stage, as shown in Fig. 6. In the elastic stage, the stiffness and the elastic modulus govern the behaviors of the joints until yielding takes place. Within this stage, the load increases rapidly with a high load/displacement ratio, which depends on the stiffness of the joint that in turn depends on the material and configuration. When the specimens are further loaded, plastic deformation appears and four obvious plastic hinges could be seen, as shown in Fig. 7. Two of the plastic hinges would appear near the weld toe, and the other two would be near the bolted area. In this stage, the deformation grows more rapidly but the resistance of the joint increases slowly. In general, it is found that the load-displacement curves from the same steel grades (Figs. 4 or 5) are generally parallel to each other in this stage. If the loads are further increased, further hardening will appear due to the large deformation of the joint that change the original configuration of the joint from T to Y shape. Meanwhile, large tensile forces will
be induced in the flanges of the T-stub joints and the parallel relationship in the load-
displacement curves tends to be disturbed. The final failure usually happened in the forms of
either weld toe through thickness fracture or bolt hole necking failure (net section failure
under tension).

3.2 The elastic stage

3.2.1 Stiffness

For design purpose, the behavior of the joints under the elastic stage and the first yield
resistance is of the most importance. From Figs. 4 and 5, it can be seen that not only the
stiffness but also the deformation limit of the elastic stage varied according to the thickness
and steel grade of the specimens. To quantitatively evaluate the effects of these two
parameters, the elastic stage and plastic hinge stage of the curves are taken out and simplified
into a straight line model (Fig. 8). The intersection of the two straight lines or the turning
point of the model is defined as the first yield resistance of the joint, which is widely accepted
as the design plastic resistance of the joint before large deformation appears [11, 14]. Based
on this simplified load-displacement model, the global stiffness of the studied T-stub joints
under the elastic stages is defined as:

\[ E_G = \frac{F_L}{d} \]  

(Eqn. 1)

where \( E_G \) is the global stiffness and \( F_L \) is the applied load (or resistance) at a certain level of
elastic displacement \( d \).

The stiffness based on the test results for all the tested joints are listed in Table 2. It can be
seen from Table 2 that the difference between the 2 tests of the same type are negligible,
implying that the test results are consistent and repeatable. The maximum differences
between specimens occurred for the 8mm and 16mm RQT-S690 specimens are only 3.2%
(row 4, Table 2). Table 2 also shows that the stiffness in terms of applied load (kN) per
displacement (mm) increased rapidly with the thickness of the specimens. The stiffness of the 16mm RQT specimens (column 4, Table 2) is about 5.3 times of that of the 8mm RQT specimens (column 2, Table 2), while the stiffness of the 22mm TMCP-S440 specimens (column 6, Table 2) is slightly less than 2 times of that of the 16mm TMCP-S385 specimens (column 5, Table 2). In addition, despite that the 16mm RQT-S690 specimens and the 16mm TMCP-S385 specimens had the same thickness, the 16mm RQT-S690 specimens showed slightly higher stiffness (columns 4 and 5, Table 2). The data in Table 2 are further plotted in Fig. 9 which clearly shows a linear stiffness-thickness relationship. Based on the test data, the equation of the trend line (Fig. 9) is obtained and expressed as:

\[ E_G = 6.520r - 40.98 \]  
(Eqn. 2)

Comparison between the test average value and the trend line prediction value is shown in row 8 of Table 2. It can be seen that the trend line equation agreed well with the test results, except for a slightly higher difference for the 16mm TMCP-S385 specimens.

3.2.2 Design plastic resistance

In EC3, to estimate the design resistance of T-stub joints, three failure modes, namely (1) complete yielding of the flange, (2) bolt failure with yielding of the flange and (3) bolt failure [14] are identified. In this study, all the specimens were failed by complete yielding of flange and only small plastic deformation was observed in the bolts for the 22mm TMCP-S440 specimens. To predict the design resistance of a T-stub joint when it is failed in complete yielding of the flange, two methods based on the yield line analysis are adopted, as specified by EC3 [14].

Method 1:  
\[ F = \frac{4M_{pl1,Rd}}{m} \]  
(Eqn. 3)

Method 2:  
\[ F = \frac{(8n-2e_w)M_{pl1,Rd}}{2mn-e_w(m+n)} \]  
(Eqn. 4)
In Eqns. 3 and 4, $M_{pl,1,Rd} = l_{\text{eff}}(\frac{m}{2})^2 f_y$ is the design moment resistance of the section. $l_{\text{eff}}$ is the effective width of the T-stub flange of the joint (Fig. 6.2 of [14], 150mm in this study), $m$, $n$ are geometrical parameters of the T-stub joints (Fig. 10). $e_w$ is either equal to 1/4 of the washer diameter or the width across points of the bolt head of nut, as relevant [14]. Note that in Method 2, instead of concentrated at the center line of the bolt, it is assumed that the force applied to the T-stub flange by a bolt is distributed uniformly under the washer (or the bolt head/nut). Since the distance between the center lines of the weld toe plastic hinge and the bolt area plastic hinge is smaller than $m$ (especially at the beginning of the plastic hinge development stage as shown in Fig. 7), this assumption leads to higher but more realistic resistance.

The design resistance of the studied T-stub joints obtained by Eqns. 3 and 4 and the actual resistance obtained from tests are shown in Table 3 and plotted in Fig. 11. Table 3 and Fig. 11 show that the design resistances of the RQT specimens are superior when compared with the TMCP specimens. The average design resistance of 16mm RQT-S690 specimens is about 91.3% more than that of 16mm TMCP-S385 specimens. However, the test results of the RQT-S690 specimens are generally lower than that predicted by the EC3 equations. The actual first yield resistance of 8mm RQT-S690 specimen when yielding occurred is lower than both Eqns. 3 and 4, and the resistances of 12mm and 16mm RQT-S690 specimens are only slightly higher than Eqn. 3 and lower than Eqn. 4. On the contrary, the test results of the TMCP specimens are approximately 20% and 11% higher than Eqns. 3 and 4, respectively. Based on these test results, it appears that the EC3 equations are conservative when predicting the design resistance for the TMCP-S385 and S440 joints but not for the RQT-S690 joints.

3.3 Plastic hinge and failure stages
From Figs. 4 and 5, it can be seen that different from the elastic stage, the stiffness of the plastic hinge stage among all the curves is comparable. The plastic stiffness (kN/mm) of all the curves in the plastic hinge stage is listed in Table 4 and plotted in Fig. 12. It can be seen from Fig. 12 that the stiffness of the RQT-S690 joints is roughly proportional to the plate thickness. The plastic stiffness of the 16mm and 12mm RQT-S690 specimens is roughly 2 and 1.6 times that of the 8mm RQT-S690 joints (Table 4), respectively. It should be noted that the plastic stiffness of the RQT joint is higher than that of the TMCP joint, which may be the result of stronger strain hardening effect of the RQT steel. As shown in the stress strain curves of the materials (Fig. 1), the RQT steel shows a more noticeable hardening stage with a higher gradient after yielding when compared with the TMCP steels.

Despite that the RQT-S690 steel has shown superior behaviors during the elastic and the plastic hinge stages when compared with the TMCP-S385 and S440 steels, the deformation capacities and the ultimate loading capacities of the RQT-S690 specimens are worse than the TMCP specimens. The load-displacement curves of the 16mm RQT-S690 and 16mm TMCP-S385 specimens are extracted from Figs. 4 and 5 and then plotted in Fig. 13. Fig. 13 shows that the load-displacement curves of these two series of specimens are very similar. They showed almost the same stiffness, similar plastic hinge and failure stages. The major differences are that both the ductility (in terms of ultimate displacement) and the ultimate load carrying capacities of the 16mm RQT-S690 joints are worse than the 16mm TMCP-S385 joints. Due to the higher ductility of the materials and the deformation capacity of TMCP plates, the 16mm TMCP-S385 specimens absorbed more strain energy and sustained larger deformation (which helped to increase the ultimate load carrying capacity by changing the shape of the joint from T to Y) before failure than the 16mm RQT-S690 joints. This also indicated that T-stub joints fabricated by using RQT-S690 steel may not be good for
applications such as earthquake resistance structures which demand high ductility and energy
dissipation/absorption capacity.

At the final failure stage of the joints, two ultimate failure modes were observed. They are the
weld toe failure mode (Fig. 14) and the bolt hole **net section failure mode** (Fig. 15). Both
failure modes are the direct results of the deformation/rotation of the plastic hinges developed.
Figs. 14 and 15 clearly show that the weld toe failure mode is more brittle with through
thickness fracture while the bolt hole failure is relatively ductile with obvious necking of the
cross section near the bolt hole openings. It should also be noted that even for the specimens
that failed by the ductile **net section failure** at the bolt holes, surface cracks (which were
caused by the welding HAZ embrittlement effect) were found at the weld toe (Fig. 16). A
summary of the failure modes of the tested specimens are listed in Table 5. From Table 5, it
can be seen that for the RQT-S690 specimens, only the thinnest 8mm joints were failed in the
ductile mode. In contrast, only one of the two **thickest** 22mm TMCP specimens was failed in
the brittle mode. As the thicker the plate the more heat inputs was applied in the welding
process, the failure mode observation somehow implies that the RQT specimens could be
more sensitive than the TMCP specimens in terms of welding HAZ embrittlement effects.

4. Yield line method for design resistance prediction

4.1 Yield line approach

Various analytical approaches with different complexities for predicting the load-
displacement relationships of T-stub joints have been developed. From plastic analysis,
Zoetemeijer [21] derived the design plastic resistance of T-stub joints. Based on his models,
many researchers have further developed the yield line theory to solve the initial stiffness and
the plastic resistance with higher accuracy [11, 13, 22]. In this paper, a yield line model is
proposed for T-stub joints made of RQT-S690 and TMCP-S385 and S440 steels. Similar to
the previous works [11, 13, 21, 22], this model focuses on the initial stiffness and the design
plastic resistance at the relatively small deformation stage of the joints.

This model starts with the assumption that the prying forces at both ends of the chord plate
are negligible. Hence, the work done by the applied load $F$ will be fully transferred as the
strain energy of the plastic hinges according to the virtual work principle.

$$Fd = W_{ph} = 4M\theta$$  \hspace{1cm} (Eqn. 5)

In Eqn. 5, $F$ is reaction force at a given displacement $d$. $M$ is the plastic hinge moment and $\theta$
is the rotation at deformation $d$ (Fig. 10).

By simple geometrical analysis,

$$d = m \tan \theta = m\theta.$$  \hspace{1cm} (Eqn. 6)

Therefore, Eqn. 5 can be simplified as

$$F = 4M/m$$  \hspace{1cm} (Eqn. 7)

Based on the stress-strain curves of the three materials obtained by standard coupon tensile
test (Fig. 1), the simplified two-stage elastic-plastic stress-stain curves are derived and are
shown in Fig. 17. The definitions of the symbols of the stress-strain curves are shown in Fig,
18a. Note that for the TMCP-S385 and S440 steels, due to their relative small hardening
behavior, the slope is set to $E_p=0$ while the slope of the RQT-S690 is set to $E_p=1.51$GPa.
Depending on the maximum strain $\varepsilon_m$ at the extreme fiber of the section, two possible
patterns of stress/strain distribution over the cross section of the plastic hinge could be
defined as shown in Fig. 18b.

When the cross section is not yielded, i.e. $\varepsilon_m \leq \varepsilon_y$, the stress $\sigma$ at a distance $x$ from the
natural axis can be expressed as

$$\sigma = E \frac{x}{t/2} \varepsilon_m$$  \hspace{1cm} (Eqn. 8)

However, when the extreme fibers of the section are yielded, i.e. $\varepsilon_m > \varepsilon_y$,
Hence, the moment of the plastic hinge can be calculated from simple integration of the stresses over the cross-section:

For $\varepsilon_m \leq \varepsilon_y$:

\[
M = 2l_{eff} \int_0^{t/2} \sigma \, dx = 2l_{eff} \left( \frac{t}{2} \right)^2 (\frac{1}{3} E \varepsilon_m)
\]

(Eqn. 10)

For $\varepsilon_m > \varepsilon_y$:

\[
M = 2l_{eff} \int_0^{t/2} \sigma \, dx = 2l_{eff} \left( \frac{t}{2} \right)^2 \left[ \frac{1}{3} E \varepsilon_m + \frac{1}{2} (E - E_p) \varepsilon_y - \frac{1}{6} (E - E_p) \frac{\varepsilon_y^3}{\varepsilon_m^2} \right]
\]

(Eqn. 11)

From elementary beam theory, the curvature of the cross section is equal to $\gamma = \frac{\varepsilon_m}{t/2}$.

Assuming that with small displacement, the length of the plastic hinge $L$ is equal to $k \frac{t}{2}$ (where $k$ is a parameter that depends on the geometry of the specimen and steel grade) and $\gamma$ is constant within the plastic hinge [22], then the rotation $\alpha$ of the plastic hinge can be calculated as

\[
\alpha = \int_0^{k \frac{t}{2}} \varepsilon_m \, dL = k \varepsilon_m
\]

(Eqn. 12)

Using Eqn. 6 and assuming $\theta = C\alpha$ and define $K = Ck$ where $C$ is a constant, Eqn. 12 can be rewritten as:

\[
\varepsilon_m = \frac{\alpha}{k} = \frac{\theta}{Ck} = \frac{d}{km}
\]

(Eqn. 13)

Thus, Eqns. 10 and 11 can be expressed as:

For $\varepsilon_m \leq \varepsilon_y$ (or $\frac{d}{km} \leq \varepsilon_y$ or $d \leq Km\varepsilon_y$):

\[
M = 2l_{eff} \left( \frac{t}{2} \right)^2 \left( \frac{1}{3} E \frac{d}{km} \right)
\]

(Eqn. 14)

For $\varepsilon_m > \varepsilon_y$ (or $d/Km > \varepsilon_y$ or $d > Km\varepsilon_y$):

\[
M = 2l_{eff} \left( \frac{t}{2} \right)^2 \left[ \frac{1}{3} E \frac{d}{km} + \frac{1}{2} (E - E_p) \varepsilon_y - \frac{1}{6} (Km)^2 (E - E_p) \frac{\varepsilon_y^3}{d^2} \right]
\]

(Eqn. 15)
Substituting Eqns. 14 and 15 into Eqn. 7, the solution for the relationship between \( F \) and \( d \) can now be expressed as

\[
F = \frac{2l_{\text{eff}}t^2}{m} \left( \frac{E}{3Km} \right) \frac{d}{Km} \quad \text{for} \quad d \leq Km \varepsilon_y \tag{Eqn. 16}
\]

\[
F = \frac{2l_{\text{eff}}t^2}{m} \left[ \frac{1}{3} E \frac{d}{Km} + \frac{1}{2} \left( E - E_p \right) \varepsilon_y - \frac{1}{6} (Km)^2 \left( E - E_p \right) \frac{\varepsilon_y^2}{d^2} \right] \quad \text{for} \quad d > Km \varepsilon_y
\]

It should be noted that after the cross section becomes fully plastic (instead of partially plastic as shown in Fig. 18b), \( M \) can be simply expressed as \( M = l_{\text{eff}} \left( \frac{t}{2} \right)^2 f_y \) so that \( F \) can be expressed as

\[
F = \frac{4l_{\text{eff}}(t/2)^2 f_y}{m} \tag{Eqn. 17}
\]

which is the same equation adopted by EC3 as the design plastic resistance of the section [14].

In general, the parameter \( K \) in Eqns. 12 to 16 depends on the geometry of the joint \((m, n\) and the size of bolt but not the plate thickness \( t \)) [22] and the steel grade used to fabricate the joints. To obtain the value of \( K \), first differentiate the elastic state expression in Eqn. 16 to obtain the expression of \( E_G \) as

\[
E_G = \frac{2l_{\text{eff}}t^2}{m} \left( \frac{E}{3Km} \right) \tag{Eqn. 18}
\]

Now by using Eqn. 18 and the average values of \( E_G \) listed in Table 2, the values of \( K \) for the TMCP-S385, TMCP-S440 and RQT-S690 T-stub joints tested in this study can be obtained and they are found to be equal to 10.6, 9.8 and 8.0, respectively. Eventually, the predicted load-displacement curves obtained by using Eqns. 16 and 17 for different RQT and TMCP T-stub joints are shown in Figs. 19 and 20, respectively. Figs. 19 and 20 show that the yield line approach (abbreviated as YL in the figures) agreed well with the TMCP test results but overestimated the strength of RQTS-690 joints after the elastic stage.

4.2 Comparison of design plastic resistance by different methods
Furthermore, based on the prediction curves obtained from the yield line model, the plastic resistances of the joints are calculated by using the graphical approach shown in Fig. 8. The results obtained are then expressed as percentage of the prediction by Eqn. 3 and are listed in Table 6. Table 6 shows that the yield line method can again predict reasonably the plastic resistances of the TMCP joints. The results of the yield line approach only slightly overestimated the plastic resistance by less than 10% while Eqns. 3 and 4 underestimated by more than 20%. However, for RQT-S690 joints, the yield line model consistently overestimated the design plastic resistance of the joint by at least 20% when comparing with the tests. Furthermore, as shown in the first three rows of Table 6, it appears that the thinner the plates, the larger the over estimations by the yield line model. For the 8mm RQT-S690 joints, the yield line approach nearly overestimated the plastic resistance by 40%.

Since for the RQT-S690 joint, the design plastic resistance of the joint is largely depended on the moment resistances of the plastic hinges, it is highly suspected that the overestimation of the plastic resistance by the yield line method was caused by the properties of the plastic hinge at the weld toe. According to the recent material property study of HSS conducted by Chiew et al. [9], the mechanical properties of the RQS-S690 HSS will be affected and deteriorated after it is exposed to high temperatures. Since welding always induces localized, large and transient heat input near the fusion zone and the HAZ, the mechanical properties of HSS will be affected and changed there. Thus, the moment resistance of the plastic hinge at the weld toe may be altered by welding and different from (less than) that at the bolt area. As a result, the moment resistance at the weld toe can no longer be predicted accurately by the yield line method. However, as the relative size of the HAZ with respect to the base metal adjacent to the HZA will be decreased when the thickness of the plate is increased, the impact of such welding effects on the accuracy of the yield line method will also be decreased. This explains why the differences between the plastic resistances predicted by the yield line
method and the test results for the 12mm and 16mm RQT-S690 joints were smaller than that
for the 8mm joints.

5. Conclusions

In this study, both experiments and analytical analysis were conducted to investigate the
tensile performance of three different grades of emerging high performance structural steels,
including the Reheated, Quenched and Tempered (RQT) grade S690 high strength steel, the
Thermal-Mechanical Controlled Processed (TMCP) grade normal S385 and S440 steel.

During the tests, the plastic resistance, ultimate loading capacities and the failure modes were
recorded. The results are then validated against the analytical yield line method developed
and the design plastic resistances provided by EC3 Part 1-8. It is found that both the yield line
method and the EC3 equations could reasonably predict the design plastic resistance for the
TMCP-S385 and S440 steel joints with the EC3 equations and yield line model
underestimated and overestimated the plastic resistance by 20% and 10%, respectively.

However, it is found that the behavior of those high strength RQT-S690 T-stub joints
behaved differently when comparing with the TMCP joints. While the stiffness of the RQT-
S690 joints at the elastic stage and plastic hinge stage are similar to that of the TMCP joints,
the plastic resistances of them are generally lower than the predictions by both the yield line
method and the EC3 equations. Further investigations showed that such differences were
largely caused by the strength reduction of the plastic hinges near the weld toe of the T-stub
joint. Furthermore, it is highly possible that it such strength reduction was caused by heat
inputs during wielding which altered the high strength steel mechanical properties there.

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References


### Table 1. Mechanical properties of the TMCP-S385, TMCP-S440 and RQT-S690 plates tested

<table>
<thead>
<tr>
<th>Strengths</th>
<th>$f_y$ (MPa)</th>
<th>$f_u$ (MPa)</th>
<th>E (GPa)</th>
<th>Elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RQT-S690 (16mm)</td>
<td>745.2</td>
<td>837.8</td>
<td>208.9</td>
<td>14.5</td>
</tr>
<tr>
<td>EN 10025-6 S690Q/QL (3mm ≤ t ≤ 50mm)</td>
<td>690</td>
<td>770-940</td>
<td>-</td>
<td>14</td>
</tr>
<tr>
<td>TMCP-S440 (22mm)</td>
<td>527.3</td>
<td>601.3</td>
<td>206.9</td>
<td>29.2</td>
</tr>
<tr>
<td>EN 10025-4 S460M/ML (16 &lt; t ≤ 40mm)</td>
<td>440</td>
<td>540-720</td>
<td>-</td>
<td>17</td>
</tr>
<tr>
<td>TMCP-S385 (16mm)</td>
<td>443.3</td>
<td>568.0</td>
<td>208.4</td>
<td>37.8</td>
</tr>
<tr>
<td>EN 10025-4 S420M/ML (t ≤ 16mm)</td>
<td>420</td>
<td>520-680</td>
<td>-</td>
<td>19</td>
</tr>
</tbody>
</table>

### Table 2. Stiffness of the joint at the elastic stage

<table>
<thead>
<tr>
<th>Thickness (mm)</th>
<th>RQT-S690</th>
<th>TMCP-S385</th>
<th>TMCP-S440</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>11.5</td>
<td>37.7</td>
<td>61.0</td>
</tr>
<tr>
<td>12</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>59.3</td>
<td>102.5</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>11.6</td>
<td>37.4</td>
<td>62.0</td>
</tr>
<tr>
<td>Diff 1(%)</td>
<td>3.2</td>
<td>-1.5</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-2.0</td>
<td>1.3</td>
</tr>
<tr>
<td>Eqn. 2</td>
<td>11.2</td>
<td>37.3</td>
<td>63.3</td>
</tr>
<tr>
<td>Diff 2(%)</td>
<td>4.0</td>
<td>0.4</td>
<td>-2.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-7.4</td>
<td>0.7</td>
</tr>
</tbody>
</table>
### Table 3. Design plastic resistance of the studied T-stub joints

<table>
<thead>
<tr>
<th>Thickness (mm)</th>
<th>Test Results (kN)</th>
<th>EC3 Eqns. (kN)</th>
<th>Diff 1(%)</th>
<th>Diff 2 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Test1</td>
<td>Test2</td>
<td>Average</td>
<td>Eqn. 3</td>
</tr>
<tr>
<td>RQT-S690</td>
<td>8</td>
<td>44.2</td>
<td>41.9</td>
<td>43.1</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>126.3</td>
<td>118.4</td>
<td>122.4</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>217.8</td>
<td>219.5</td>
<td>218.7</td>
</tr>
<tr>
<td>TMCP-S385</td>
<td>16</td>
<td>146.5</td>
<td>142.0</td>
<td>144.3</td>
</tr>
<tr>
<td>TMCP-S440</td>
<td>22</td>
<td>320.3</td>
<td>317.1</td>
<td>318.7</td>
</tr>
</tbody>
</table>

For Eqns. 3 and 4, the nominal yield strengths are used. That is, \(f_y=690\), 385 and 440 MPa for RQT-S690, TMCP-S385 and S440, respectively.

\[
\text{Diff 1} = \left(\frac{\text{Average-Eqn. 3}}{\text{Eqn. 3}}\right) \times 100\%
\]

\[
\text{Diff 2} = \left(\frac{\text{Average - Eqn. 4}}{\text{Eqn. 4}}\right) \times 100\%
\]

### Table 4. Plastic stiffness of tested joints

<table>
<thead>
<tr>
<th>Thickness (mm)</th>
<th>RQT-S690</th>
<th>TMCP-S385</th>
<th>TMCP-S440</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plastic Stiffness (kN/mm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Series 1</td>
<td>4.6</td>
<td>7.3</td>
<td>9</td>
</tr>
<tr>
<td>Series 2</td>
<td>4.5</td>
<td>7.1</td>
<td>8.5</td>
</tr>
</tbody>
</table>
Table 5. Failure modes of the tested joints

<table>
<thead>
<tr>
<th>Thickness (mm)</th>
<th>RQT-S690</th>
<th>TMCP-S385</th>
<th>TMCP-S440</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weld toe brittle failure</td>
<td>S1;S2</td>
<td>S1;S2</td>
<td>S1</td>
</tr>
<tr>
<td>Bolt hole ductile failure</td>
<td>S1;S2</td>
<td>S1;S2</td>
<td>S2</td>
</tr>
</tbody>
</table>

S1 and S2 refer to T-stub Specimen 1 and T-stub Specimen 2, respectively.

Table 6. Design plastic resistance predicted by different methods

<table>
<thead>
<tr>
<th>Series</th>
<th>Eqn. 3 (%)</th>
<th>Eqn. 4 (%)</th>
<th>YL Model (%)</th>
<th>Test1 (%)</th>
<th>Test2 (%)</th>
<th>Taver (%)</th>
<th>Diff. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RQT-S690 8mm</td>
<td>100</td>
<td>107.1</td>
<td>120.4</td>
<td>89.5</td>
<td>84.8</td>
<td>87.2</td>
<td>38.2</td>
</tr>
<tr>
<td>RQT-S690 12mm</td>
<td>100</td>
<td>107.2</td>
<td>127.7</td>
<td>107.6</td>
<td>103.3</td>
<td>105.5</td>
<td>21.1</td>
</tr>
<tr>
<td>RQT-S690 16mm</td>
<td>100</td>
<td>107.3</td>
<td>124.8</td>
<td>103.6</td>
<td>104.4</td>
<td>104.0</td>
<td>20.1</td>
</tr>
<tr>
<td>TMCP-S385 16mm</td>
<td>100</td>
<td>107.3</td>
<td>133.0</td>
<td>124.9</td>
<td>121.1</td>
<td>123.0</td>
<td>8.1</td>
</tr>
<tr>
<td>TMCP-S440 22mm</td>
<td>100</td>
<td>107.5</td>
<td>130.8</td>
<td>120.3</td>
<td>119.1</td>
<td>119.7</td>
<td>9.2</td>
</tr>
</tbody>
</table>

All predictions are expressed as percentage of the predicted values by Eqn. 3.

Taver = (Test1+Test2)/2

Diff. (%)=(YL Model - Taver)/Taver×100%
Fig. 1. Stress-strain curves of different steels

Fig. 2. Configuration of the T-stub joints
Fig. 3. The T-stub joint test setup

Fig. 4. Load-displacement curves of the TMCP-S385 and S440 T-stub joints
Fig. 5. Load-displacement curves of the RQT-S690 T-stub joints

Fig. 6. Typical load-displacement curve of the tested T-stub joints
Fig. 7. Plastic hinges formation

Fig. 8. Simplified elastic-plastic load-displacement curve and design plastic resistance of T-stub joint
Fig. 9. Stiffness of joints during the elastic stage

Fig. 10. Force diagram for design plastic resistance calculation
Fig. 11. Design plastic resistance of tested joints

Fig. 12. Stiffness of the joints during the plastic hinge stage
Fig. 13. Load-displacement curves of the 16mm RQT-S690 and TMCP-S385 joints

Fig. 14. Brittle weld toe through thickness fracture (12mm RQT-S690 joint)
Fig. 15. Ductile net section failure under tension (8mm RQT-S690 joint)

Fig. 16. Surface cracks at the weld toe (8mm RQT-S690 joint)
Fig. 17. Simplified stress-strain curves for the yield line approach

(a) Stress-strain model

(b) Stress distributions in the section of the plastic hinges

Fig. 18. Stress-strain models and stress distribution at plastic hinge locations
Fig. 19. Comparisons of the load-displacement curves for RQT-S690 joints

Fig. 20. Comparisons of the load-displacement curves for TMCP joints