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Effects of Welding on the Tensile Performance of High Strength Steel T-stub Joints

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ABSTRACT

In this study, the effects of welding on the tensile performance of the Reheated, Quenched and Tempered (RQT) S690 high strength steel T-stub joints are investigated by both experimental and numerical methods. Firstly, six RQT-S690 T-stub joints as well as two Thermal-Mechanical Controlled Processed (TMCP) S385 T-stub joints are fabricated and tested. The results are validated against the design plastic resistance equations provided by EC3. It is found out that EC3 predicts the plastic resistance of the TMCP joints conservatively, but tends to overestimate that of the RQT-S690 joints although the latter is much superior. It is deducted that the problem may come from the compromised properties of the heat affected zone (HAZ) at the weld toe. Further, finite element analysis is carried out to investigate the effects of property alteration in the HAZ on the tensile performance of the RQT-S690 T-stub joints. It is shown that the models with welding simulation agree well with the test results, while the models without considering the welding effects predict the load carrying capacity unconservatively when the displacement increases.

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 [1]. With the development of design, fabrication and technology, the evolution of steels for construction never stops. In the 1900s, most primary structural steel only had nominal yield strengths of about 220 MPa, which is equivalent to today's "mild steel" [2]. The once so called "high strength" steel S355 is now a widely used structural material. In fact, steels with yield strength up to 460 MPa have been commonly specified for applications in many structural design codes [3,4]. What is more, the interest for using high strength (HSS) with minimum yield strength >460 MPa in application have been increasing in the last decade.

Strength of steel is usually enhanced by either adding alloying elements or going through heat treatments/work hardening. Different from high alloy steels, heat treated steels offer better performance in yield and tensile strength without sacrificing much weldability, e.g., low alloy quenched and tempered HSS in grade S690. For many types of HSS such as the quenched and tempered S690 steel, the actual yield strength can be easily double that of grade S355 normal strength steel (NSS). However, HSS differs from NSS in much more aspects than just strength. One major issue against the popularization of HSS is that the quenching and tempering process improves the strength at the expense of ductility through complicated heat treatments. Massive researches have demonstrated that it is not possible for QT steels to achieve good deformation capacity [2,5,6] and they are more susceptible to heat [7,8] than mild steels, as inherited from the heat-treatment hardened microstructures [9]. Accordingly, it is not surprising that concerns are raised about the performance of welded high performance steel connections, especially when large heat input welding is applied [10]. For conventional steels, it is suggested that if the width of the soft zone does not exceed 25% of the plate thickness, the local softening would not necessarily impair the global strength due to the constraints of the stronger weld metal and unaffected base metal [11,12]. However, this criterion may not apply on high performance steels, because their main constitutes in the microstructures, such as martensite and bainite, are not stable at high temperatures [13]. There is a possibility that the enhanced mechanical properties acquired by means of hardening may deteriorate significantly after exposure to heat, due to microstructural changes at certain critical temperatures [9,14].

The objective of this paper is to investigate the effect of welding on the tensile performance of high strength steel, i.e. Reheated, Quenched and Tempered (RQT) Steel in grade S690 by both experimental and numerical methods. As control material, the Thermal-Mechanical Controlled Processed (TMCP) steel in grade S385 is employed in the experimental program. Eight T-stub joints in the same configuration but different materials and thicknesses are fabricated and tested. Based on the test results in terms of load-displacement curves, the

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first yield resistance is obtained and compared with predictions by design equations provided by EN 1993-1-8 [15]. Further, finite element simulation is carried out to investigate the influence of welding induced HAZ on the tensile performance of the RQT-S690 joints. By comparing the load-displacement curves and the first yield resistance, the effects of welding on the high strength steel T-stub joints are evaluated.

2. Experimental study

2.1. Materials

The RQT is essentially a refined quenching and tempering technology. Compared with traditional directly quenched and tempered steel plates, RQT steel plates exhibit better homogeneity in through-thickness mechanical properties. The RQT grade S690 steel (RQT-S690, 8 mm, 12 mm and 16 mm thick) studied in this paper have a nominal yield strength of 690 MPa, a tensile strength from 790 MPa to 930 MPa and an elongation capacity about 15%. Besides the RQT-S690 as the main research target, another NSS in grade S385 (16 mm thick) is also tested with the same test program as the control material. This NSS is a type of advanced low alloy structural steel plate product manufactured by the Thermal-Mechanical Controlled Process (TMCP). The concept of TMCP combines controlled hot rolling with accelerated cooling to control the microstructure [16]. The goal of TMCP is to produce cost-efficient steel strips and plates with properties required for a specific application. In addition to strength, hardness and toughness, weldability and corrosion resistance are usually made features of TMCP. The TMCP-S385 tested in this study has minimum yield strength of 385 MPa and tensile strength between 550 MPa and 670 MPa.

The stress-strain curves and the summarized mechanical properties of the steel plates obtained by standard coupon tensile test are shown in Fig. 1 and Table 1, respectively. Table 1also compares the materials properties of the TMCP and RQT plates with the corresponding standards of EN 10025-4 [17] and EN 10025-6 [18], 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, which is widely used in construction. Second, RQT-S690 steel is relatively brittle compared to traditional NSS and the TMCP-S385 tested in this study. It can also be seen from Table 1 that the TMCP-S385 steel literally fulfilled the mechanical property specifications of S420 M/ML steel.

2.2. T-stub joint specimen fabrication

Four types of T-stub joints were fabricated. They were of the same configuration but fabricated by using different materials and plate thickness: RQT-S690 (8 mm, 12 mm and 16 mm) and TMCP-S385

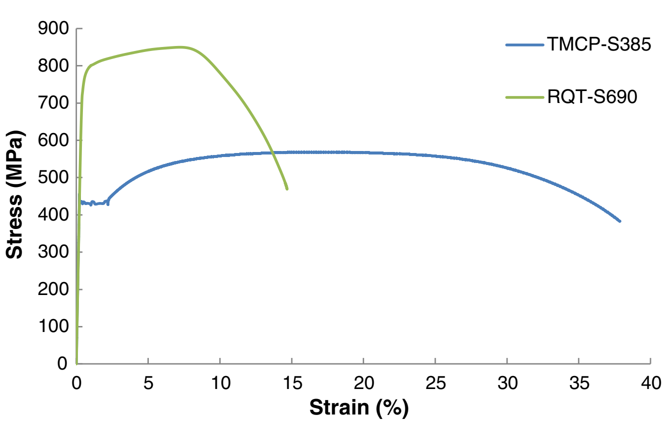

Fig. 1. Stress-strain curves of RQT-S690 and TMCP-S385.

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

	f_y(MPa)	f_u(MPa)	E (GPa)	Elongation (%)
RQT-S690 (16 mm)	745.2.0	837.8	208.9	14.5
EN 10025-6 S690Q/QL (3 mm ≤ t ≤ 50 mm)	690	770–940	–	14
TMCP-S385 (16 mm)	443.3	568.0	208.4	37.8
EN 10025-4 S420M/ML(t ≤ 16 mm)	420	520–680	–	19

(16 mm). For each type of T-stub joint, two same specimens were fabricated and tested so a total of eight 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 to finish the welding connection. 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 2000 kN. To fix the specimen into the test machine, "inverted" support joints made of S355 steel plates with thickness of 50 mm 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. It should be noted that in certain situations, the response of T-stub joints is influenced by the type of bolt assembly. The rational selection of the most suitable bolt type according to the specific structural usage may avoid premature reduction of joint strength for higher levels of joint rotation and provide further rotational capacity [21]. In this study, the consideration in the selection of bolt is to guarantee the bolts work elastically and cause little influence to the load-displacement relationship. This assumption was verified during testing since no obvious plastic deformation was caused to the bolts after unloading.

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 1 mm/min for all time so that quasi-static response could be obtained.

2.4. Test results

2.4.1. General descriptions

Fig. 4 presents the test results in terms of the load-displacement curves of the RQT-S690 (8 mm, 12 mm and 16 mm) T-stub joints, while the test results of the TMCP-S385 (16 mm) joint are shown in Fig. 5 in comparison with those of the RQT-S690 (16 mm). Despite that the specimens may fail in different modes 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

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