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Impact of welding on the strength of high performance steel T-stub joints

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ABSTRACT

In this study, experiments were carried out to investigate the influence of welding on the strength of the reheated, quenched and tempered (RQT) steel S690 and the thermo-mechanically controlled processed (TMCP) steel S385. Firstly, a specially designed welding procedure was applied to produce RQT and TMCP steel plates that were fully affected by the welding heat input for the whole plate thickness. These fully weld-affected plates were then fabricated into specimens for tensile test and metallurgical examination including microstructure observation and Vickers hardness measurement. The results showed that welding softened the heat affected zone of the RQT-S690 steel significantly but its effect on the TMCP-S385 steel was insignificant. Secondly, T-stub joints were fabricated by using the RQT and TMCP steel plates and tested in tension until failure. The design plastic resistances of the joints are then compared with the prediction by EC3 equations. It is found that the EC3 equations could produce unsafe prediction for the RQT joint. Based on the test results, a reduction factor is proposed to modify the EC3 equations to produce reasonable conservative prediction of the RQT joint design plastic resistance.

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1. Introduction

Due to its high strength, high stiffness and ductile properties, structural steel is one of the most popular construction materials employed in structural engineering [1]. Recently, with the rapid advancement in thermal and mechanical processing procedures for structural steel production, the interest for using high strength steels (HSS) with minimum yield strength >460 MPa has been increasing in the last decade [2]. In fact, normal strength steels (NSS) with yield strength up to 460 MPa have been commonly specified for applications in many structural design codes [3,4]. The most commonly referred performance characteristics of structural steel are their mechanical and chemical properties, metallurgical structures and weldability [2]. In many structural applications, traditional focus is the tensile performance (yield stress and ultimate tensile stress) of the steel. However, after many disasters involving fatigue loading, earthquake, serious fire and terrorist attacks, the emphasis of tensile performance characteristics became more frequently questioned while other performance-improving properties under extreme loading conditions such as deformability and post-fire performance received more and more attentions.

Modern high performance structural steels are usually the product of advanced heat treatment and characterized by increased strength and toughness together with low carbon equivalents [5]. Different from high alloy steels, the weldability of heat treated steels is improved significantly in the sense of reduced pre-heating requirements and reduced susceptibility to cold cracking [6]. As a result, higher design flexibility and construction productivity can be achieved. For conventional steel plates, it is suggested that if the width of the soft zone does not exceed 25% of the plate thickness, local softening would not necessarily impair the global strength due to the constraints of the stronger weld metal and unaffected base metal [7,8]. However, such assumption may not be applied to high performance steels because their main microstructure constitutes, such as martensite and bainite, are not stable at high temperatures [9]. 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 [10,11]. This undesirable property was first confirmed for work hardened cold-formed hollow sections [12], and then later for the high strength steel S460 and S690 [13] as well as the cold rolled steel Bisplate 500 [14]. As a result, it is not surprising that concerns are raised about the performance of welded high performance steel connections, especially when high heat input welding is applied [15].

The main objective of this paper is to experimentally investigate and compare the influence of welding on the strength of two relatively new high performance structural steels, namely the reheated, quenched and tempered (RQT) high strength steel grade S690 (RQT-S690) and the thermo-mechanically controlled processed (TMCP) normal strength

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steel grade S385 (TMCP-S385). The whole study is divided into two phases. In the first phase, a specially designed welding procedure is developed and applied to both the RQT690 and TMCP385 steel plates in order to induce full welding heat effect in the plate's thickness direction. These fully weld-affected plates are then fabricated into standard size specimens for tensile test and metallurgical examination including microstructure observation and micro-hardness test. In the second phase, the tensile performance of welded T-stub joints fabricated by using the RQT-S690 and the TMCP-S385 plates are studied. The load-displacement curves, failure modes, first yield resistance of the tested specimens and plastic stage behaviour are investigated. By comparing the first yield resistances obtained from the test and the design plastic resistances predicted by the EC3 equations, the effects of welding on the joint strength of the specimens are evaluated. Furthermore, based on the test results, a new reduction factor which will take account for the welding effect is proposed to provide reasonable conservative predictions of the plastic resistance of HSS RQT-S690 T-stub joints.

2. Phase 1: material property of fully weld-affected specimens

2.1. Base metal

In the first phase, 16 mm thick TMCP-S385 and RQT-S690 steel plates with minimum yield strengths of 385 MPa and 690 MPa respectively are examined. TMCP is an advanced thermo-mechanical process to produce low carbon plate steels "microalloyed" with Ti, Nb and V. The production concept of TMCP is to combine controlled hot rolling with accelerated cooling to generate a bainite and ferrite dominating microstructure [16]. By using the merits of grain refinement, precipitation hardening and low amount of transformation hardening, the TMCP enables the production of as-rolled steels (i.e. no offline transfer is needed during the production process) with final properties that are tailored to the requirements and specifications of the target application [17]. In addition to strength, hardness and toughness, weldability and corrosion resistance are usually made features of TMCP. The TMCP-S385 steel plates tested in this study has minimum yield strength of 385 MPa and tensile strength between 550 MPa and 670 MPa. The RQT690 plates used in this study are manufactured by a refined quenching and tempering technology. Similar to the conventional quenched and tempered steels, RQT steels also depend on the extremely fast cooling to produce martensite in the microstructure to enhance their strengths [10]. However, RQT steel plates exhibit better homogeneity in through-thickness mechanical properties compared with traditional directly quenched and tempered steel plates. The RQT-S690 steel plates studied in this paper comply with the EN 10025-6 grade S690 specification [18] and have minimum yield strength of 690 MPa and tensile strength between 790 MPa and 930 MPa.

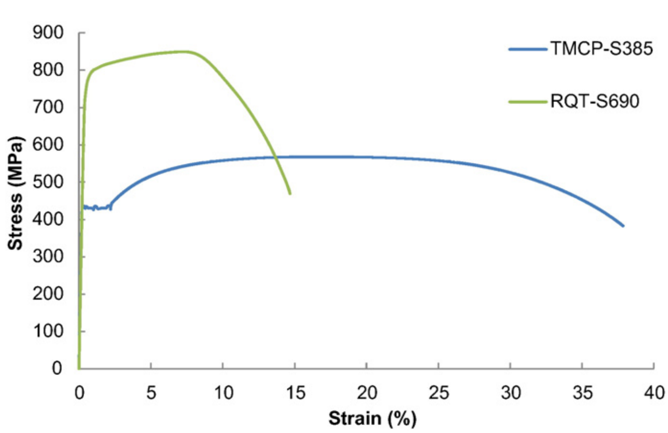

Fig. 1. Stress-strain curves of RQT-S690 and TMCP-S385 steels.

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

Strengths	f_y (MPa)	f_u (MPa)	E (GPa)	Elongation (%)
RQT-S690 (16 mm)	745.2	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 S420 M/ML(t ≤ 16 mm)	420	520–680	–	19

t = thickness of plate.

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 properties of the RQT and TMCP plates with the respective standards of EN 10025-6 [18] and EN 10025-4 [19]. From Table 1, it can be seen that RQT-S690 steel's yield strength is almost twice the yield strength of S355 but both of its elongation at fracture and tensile ratio are lower when compared with traditional normal strength steel and the TMCP-S385 steels. Table 1 also indicates that the TMCP-S385 steel literally fulfilled the mechanical property specifications of the slightly higher grade S420M/ML steel.

2.2. The fully weld-affected plate

Theoretically, the mechanical properties of material within the heat affected zone (HAZ) can be assessed by direct examination of a very small size sample from the welded joints. However, this method presents many difficulties in practice, such as the needs of delicate positioning and extraction of a very small size sample from the HAZ within a narrow zone with high microstructure gradients. Hence, the material properties within the HAZ zones are often assessed by performing experiments on test samples that undergone simulated thermal treatments closely resemble that experienced in the HAZ [20]. The main idea of the HAZ material property test in this study is to manufacture and examine the properties of plates that have been fully affected in the thickness direction by the heat input during welding. In order to ensure that the HAZ is fully developed through the thickness of the specimens, a special welding process was designed: Welding was first carried out on both sides of the 800 mm × 300 mm × 16 mm specimen plates (Fig. 2). The welding was carried out in the center area of the plate along the longitudinal direction and covered a width of 120 mm long. Shielded Metal Arc Welding (SMAW) and a single electrode LB-70L were employed to finish the welding at a voltage of 26 V using a current of 170A and welding speed of 2.2 mm/s. The equivalent heat input is about 2.0 kJ/mm. Special caution was also paid to the welding sequence to minimize the deformation and residual stress associated with uneven heating and cooling. As shown in Fig. 2, every time when two passes

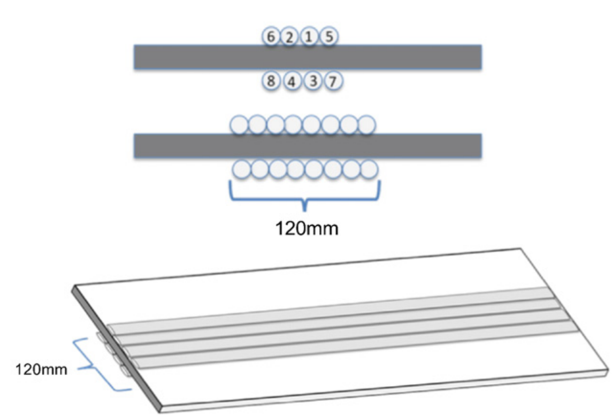

Fig. 2. Welding procedure for the fabrication of fully weld-affected plates.

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