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EFFECT OF WELDING ON THE TENSILE BEHAVIOR OF HIGH STRENGTH STEEL T-STUB JOINTS

- PART II: NUMERICAL STUDY

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\textbf{Keywords:}
Effect; Welding; Tensile Behavior; High Strength Steel; T-stub Joints

\begin{tabular}{c}
\textbf{A B S T R A C T} \\
This paper numerically investigated the impact of welding with large heat input on the tensile strength of high strength steel S690 T-stub joints. Finite element simulation was employed to simulate the two-pass thermal-mechanical welding process. Focus was given to the deterioration of mechanical properties in the heat affected zone and its effect on the tensile performance of the whole joint. The simulation results in terms of load-displacement curves are compared with the test results of the high strength steel S690 T-stub joints stated in part I of this twin paper. It is found that the mechanical property deterioration in the heat affected zone of high strength steel caused by welding is remarkably harmful to the global tensile performance of the studied T-stub joints.
\end{tabular}

1 INTRODUCTION

High strength steel (HSS) attracts more and more attention for construction for its higher strength to weight ratio, which contributes to better architectural expression and lower labor and transportation costs. Until now, there are not many structures using HSS. Even the famous HSS structures such as Skytree tower in Tokyo, truss structure of the Sony Center in Berlin and Akashi Kaikyo Bridge(Miki, Homma, & Tominaga, 2002) do not use HSS in a large portion of the whole structure.

Commonly, high strength steel is only available in the form of plate due to the limitation of producing process. As a result, HSS plates have to be welded into built-up sections for structural usage. Two kinds of welding procedure are usually adopted for building structural steel sections according to the amount of heat input. One is small heat input welding with multiple passes. The other is large heat input welding with single or double passes. Small heat input has less significant effect on the base material but costs more labor work. On the other hand, large heat input leads to less welding time but bigger heat affected zone (HAZ) where the microstructure and characteristics of base material may change seriously (Gunaraj & Murugan, 2002).

For high strength steel, the change of microstructure in the HAZ affects but is not limited to toughness, strength and ductility. Coupon tests have show that the yield strength of high strength steel (S690) reduce almost 50% after cooling down from 850°C (Chiew, Zhao, & Lee, 2014; Qiang, Bijlaard, & Kolstein, 2012) which the HAZ certainly has to pass during welding. For welded HSS butt joint, the ultimate tensile strength decreases by 8% due to the big soft zone in HAZ caused by large heat input welding (Hochhauser & Rauch, 2012). However, large heat input welding method is still preferred in workshop due to the demand of higher productivity.

In this paper, two finite element models are built to simulate the welding process for welded HSS S690 T-stub joints. One model is built with whole welding process and quasi-static tensile process. The material deterioration of HSS after exposure of high temperature is also taken into consideration. The other model is built without consideration of the effect of welding. The simulation results are compared with experimental data from the tensile test of welded HSS T-stub.

2 FINITE ELEMENT MODEL

The two HSS T-stub models are built by using ABAQUS. In order to gain accurate numerical results to compare with experimental data, bolts (Grade 10.9, M24) and supporter are also simulated in the models. The HSS T-stub, used in experiment, is welded with small heat input
and multiple passes. The dimension of specimen is shown in Figure 1.

![Figure 1. T-stub model.](image)

Sequentially coupled thermal-stress analysis is employed to achieve the two passes welding with large heat input. Sequentially coupled thermal-stress analysis consists of two interrelated analysis processes: thermal analysis and stress analysis (Deng, 2009). Firstly, the temperature distribution and history of specimen during welding process are calculated in thermal analysis model. Then, the thermal analysis results are imported into stress analysis model as temperature load. In the stress analysis model, deformation and stress distribution caused by welding are calculated. After the welding process, displacement load is applied on the end of web plate to gain the tensile strength of HSS T-stub.

### 2.1 Heat source

In thermal analysis model, double-ellipsoid heat source, as shown in Figure 2, is defined by using subroutine DFLUX.

![Figure 2. Double-ellipsoid heat source.](image)

The heat flux $q$ is represented by the following equations:

For the front part of heat source

$$q(x, y, z, t) = \frac{6\sqrt{3}Qf_1}{ab\sqrt{\pi}} e^{-\frac{3x^2}{a^2} - \frac{3y^2}{b^2} - \frac{3z^2}{c_1^2}}$$  \hspace{1cm} (1)

For the rear part of heat source

$$q(x, y, z, t) = \frac{6\sqrt{3}Qf_2}{ab\sqrt{\pi}} e^{-\frac{3x^2}{a^2} - \frac{3y^2}{b^2} - \frac{3z^2}{c_2^2}}$$  \hspace{1cm} (2)

In the equations, $f_1$ and $f_2$ are heat distribution coefficients. It is assumed that $f_1$ is equal to 1.0 as same with $f_2$. The parameters $a$, $b$, $c_1$ and $c_2$ represent the dimensions of molten pool, which are 8.0mm, 17.0mm, 8.0mm and 16.0mm, respectively. The heat input power $Q$ ($Q = UI$) is equal to 25.6kJ/s. In view of the energy dissipation during welding, the energy efficiency coefficient is assumed to be 0.8. Additionally, welding speed is 4mm/s, and there is no interruption between the two pass welding.

### 2.2 Material properties of HSS

The material properties of HSS can be divided into two groups: mechanical properties and thermal properties. The two groups of material properties are used in corresponding analysis processes: stress analysis and thermal analysis. The mechanical properties include expansion, elastic modulus and yield strength, while thermal properties consist of density, thermal conductivity, specific heat and latent heat.

In this study, RQT-S690 HSS is chosen as the material of T-stub model. The mechanical properties at elevated temperatures and after exposure of high temperatures can be obtained from existing literatures. Figure 3 shows the stress-strain curves of S690 HSS at elevated temperatures employed in models (Chiew et al., 2014).
Figure 3. Stress-strain curves of S690 HSS at elevated temperatures.

The stress-strain curves of RQT-S690 HSS after exposure of high temperature are calculated based on a series of reduction factor expressions (Qiang et al., 2012) and corresponding formulas (Tao, Wang, & Uy, 2012), as described in Figure 4.

Figure 4. Stress-strain curves of S690 HSS after exposure of certain high temperatures.

The mechanical properties (eg., elastic modulus, yield strength, stress-strain curves) during cooling process are obtained by linear interpolation of material properties at the highest temperature which a node go through during welding process and those after cooling down to room temperature. The change of mechanical properties is achieved by two subroutines (UEXPAN and USDFLD). In subroutine UEXPAN, the highest temperature of every node is recorded and sent to subroutine USDFLD. Then, based on the highest temperature, a corresponding set of mechanical properties is assigned to the point. In this way, the material deterioration is also realized in the area around welds.

There are several advantages by combining subroutine USDFLD and UEXPAN to achieve material deterioration in HAZ compared with traditional simulation method that the material properties obtained from hardness test and are assigned to the area of HAZ which is cut out from model according to experimental data (Khurshid, Barsoum, & Barsoum, 2015). Firstly, the affected area is determined incidentally during thermal analysis. Secondly, the material properties of HSS change according to the highest temperature during stress analysis. Hence, there is no need to conduct experimental test to determine the area and corresponding hardness of HAZ.

The expansion strain of RQT-S690 is also defined in subroutine UEXPAN according to Eurocode 3, Part 1-2 (de Normalización, 2005a) as follows:

For $20^\circ$C $\leq T < 750^\circ$C

$$\varepsilon_T = 1.2 \times 10^{-5} T + 0.4 \times 10^{-6} T^2 - 2.416 \times 10^{-4}$$ (3)

For $750^\circ$C $\leq T \leq 860^\circ$C:

$$\varepsilon_T = 1.2 \times 10^{-2}$$ (4)

For $750^\circ$C $< T \leq 1200^\circ$C:

$$\varepsilon_T = 2 \times 10^{-5} T - 6.2 \times 10^{-3}$$ (5)

Additionally, the thermal properties of RQT-S690 HSS (eg., density, thermal conductivity, specific heat and latent heat) are defined as same with those of mild steel based on Eurocode 3, Part 1-2.

2.3 Mesh, element type, contact and boundary condition

The T-stub models are built by using solid element. In order to get more accurate results, the bolts and supporter are also simulated. The mesh of whole model is depicted in Figure 5. The mesh is refined around weld and bolt holes where failure is supposed to occur. Converting elements are used to connect the fine mesh and coarse mesh.

Figure 5. Mesh and physical boundary condition of FE model.

The T-stub is divided into 37584 elements, and there are 816 elements for each bolt and 1602 elements for supporter. DC3D8 (an 8 node linear heat transfer brick) and C3D8 (An 8-node linear brick) are adopted as element type in thermal and stress analysis model separately.

“Hard” contact is defined for normal behavior of contacts among T-stub, bolts and supporter. In view of the complexity of tangential behavior in contacts (eg., rough surfaces and pre-tension force in bolts), a simplified contact is adopted. Penalty friction is defined as the tangential behavior of contacts with a friction coefficient 0.3, and the pre-tension forces in bolts are ignored.

Thermal and physical boundary conditions are defined in thermal and stress analysis models separately. The room temperature is assigned as $25^\circ$C. Convection and radiation
boundary assigned on the surfaces of T-stub with the coefficients $25\text{W/(m}^2\cdot\text{°C)}$ and 0.3, respectively. The physical boundary conditions of models are assigned as same with those in experiment as shown in Figure 5. The supporter is fixed at bottom, and the top end of T-stub is fixed except for the vertical direction in which the displacement load is applied.

3 RESULTS AND DISCUSSION

The temperature distribution and history of T-stub during welding and after cooling down are obtained by thermal analysis. Figure 6 shows the temperature distribution during welding.

![Figure 6. Temperature distribution of HSS T-stub during welding.](image)

The stress contour of HSS T-stub during welding is depicted in Figure 7. It can be observed that the stress in welds is quite low because the strength of HSS decreases significantly at high temperatures.

![Figure 7. Stress contour of HSS T-stub during welding.](image)

The failure mode is yielding of flange plate which is same with that of HSS T-stub in experiment, as shown in Figure 8. It is obvious that four yield lines generated around welds and bolts.

![Figure 8. Failure mode of S690 HSS T-stub under tensile load.](image)

### 3.1 Results and Discussion

The tensile strength of T-stub can be calculated in the condition of flange yielding by using the expression as follow:

$$F_T = 0.5 \times l_{eff} t_f^2 f_y/m$$

In the expression, $l_{eff}$ is the width of flange plate, $m$ stands for the distance between weld toe and center of bolt hole, $t_f$ is the thickness of flange plate, and $f_y$ is the yield strength of steel. The geometrical parameter values and calculated tensile strength of T-stub are listed in Table 1. The yield strength of RQT-S690 HSS is obtained by coupon test.
Table 1. Geometrical parameter values and calculated tensile strength of T-stub

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<thead>
<tr>
<th>$F_t$ (kN)</th>
<th>$f_t$ (MPa)</th>
<th>$l_{eff}$ (mm)</th>
<th>$t_r$ (mm)</th>
<th>$m$ (mm)</th>
</tr>
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<tr>
<td>117.2</td>
<td>769</td>
<td>150</td>
<td>16</td>
<td>126</td>
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Figure 9 shows the comparison of load-displacement curves from FE results and experimental data. It is found that the load of FE model without consideration of material deterioration around welds is higher than that of experimental specimen. It is reasonable that welding induces material deterioration around welds in flange plate. With the increase of displacement, the higher load is necessary for experimental specimen compared with FE model to gain the same displacement due to the improved elongation of RQT-S690 HSS after exposure of high temperature around welds. It is also obvious that the tensile strength of welded T-stub with large heat input is lower than test results, because the larger HAZ is formed during welding. The comparison between FE results show that maximum decline of tensile load is 19% for HSS T-stub welded with large heat input. However, the tensile strength is still larger than the calculated value based on Eurocode 3.

4 SUMMARY AND FUTURE WORKS

This study focuses on the impact of large heat input on the tensile strength of HSS T-stub. Two finite element models are built with and without consideration of large heat input. The analysis results are compared with experimental ones from a HSS T-stub welded with small heat input and multiple passes. It can be summarized as follows:

1. The material deterioration of HSS caused by welding can be achieved by material change programs written in subroutine UEXPAN and USDFLD.
2. Material deterioration caused by welding in HAZ can reduce the tensile strength of T-stub to some extents.
3. The T-stub welded with 16mm thickness S690 HSS plate loses 19% tensile strength due to material deterioration induced by large heat input welding.

In future, more work will be done on experimental tests of HSS T-stub welded with large heat input and corresponding finite element simulation. It is expected that the relationship between area of HAZ and reduced tensile strength is obtained by numerical parameter analysis.

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6 REFERENCES