NUMERICAL STUDY ON THE INFLUENCE OF WELDING ON S690Q HIGH STRENGTH STEEL BUTT JOINTS

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In this study, the influence of welding on S690Q high strength steel (HSS) butt joints is investigated numerically by using ABAQUS. A new simulation method is proposed based on sequentially coupled thermal-stress analysis method, considering the inhomogeneous material property of HAZ which is highly affected by the peak temperature and cooling rate of welding thermal cycles. The material properties of S690Q HSS defined in the proposed model consists of stress-strain curves at elevated temperatures and after cooling down from different peak temperatures with different cooling rates. Three user-defined subroutines DFLUX, USDFLD and UEXPAN are created to achieve the inhomogeneous material properties of HAZ. The simulation method is then verified by comparing the temperature history, failure modes, and coupon test stress-strain curves obtained from experimental results of S690Q HSS butt joints with 8 mm plate thickness. Finally, based on the verified simulation method, a preliminary parameter study is conducted to explore different welding setting to eliminate the adverse effect of welding on HSS butt joints. It is indicated that well-controlled cooling rate can reduce the softening effect of welding on the tensile performance of HSS butt joints efficaciously.

Keywords: Numerical Simulation, high strength steel, butt joints, welding, tensile strength.

1 Introduction

High strength steel (HSS), as an alternative of normal strength steel in some structural engineering applications, has advantages of high strength to weight ratio, good corrosion resistance, excellent architecture expression and favorable economic benefits (Qiang, Bijlaard, and Kolstein 2012, Miki, Homma, and Tominaga 2002). In market, HSS is generally available in form of plate due to the limitation of the manufacturing process for achieving a highly uniform through thickness material properties. Consequently, extensive welding is almost inevitable for all built-up HSS sections. This implies severe temperature changes will be induced around the welding area, especially within the heat affected zone (HAZ). Previous investigations revealed

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that HSS was quite sensitive to high temperatures and its strength deteriorated with the increase of temperature (Chen, Young, Uy 2006, Chiew, Zhao, Lee 2014). Worse still, the mechanical property of HSS cannot recover to its initial state after cooling down from high temperatures (Qiang, Bijlaard, and Kolstein 2012). As a result, the mechanical behaviour of welded HSS joint was adversely affected by the welding process (Kurc-Lisiecka, Piwnik and Lisiecki 2017). It was found that higher welding heat input was accompanied by a bigger HAZ with weaker mechanical properties (Loureiro 2002, Shi and Han 2008) which directly reduced the tensile strength of welded HSS butt joints to some extent (Rodrigues, Menezes, Loureiro A, et al 2004, Hochhauser and Rauch 2012). In this study, the welding effect on the tensile behaviour of S690Q HSS butt joints is studied numerically. The proposed simulation method is first verified by comparing with experimental results of S690Q HSS welded butt joints in terms of temperature history curves, failure mode, and stress-strain curves. After this, a preliminary parameter study is carried out to reveal the influence of cooling rate on the tensile strength of HSS butt joints by using the validated numerical model.

2 Model Verification

2.1 S690 HSS Butt Joints in Experimental Study

Three verification models are established by using sequentially coupled thermal-stress analysis in ABAQUS according to the tested S690Q HSS butt joints used in the experimental study. The three welded butt joints, having same geometric dimensions as shown in Figure 1, are all fabricated by using four-pass welding, but with different welding heat inputs as listed in Table 1. During welding, thermal couples were employed to measure the temperature history of the butt joints around the welding area. After the welded S690Q HSS butt joints were cooled down to room temperature, two coupons were machined out of each joint for standard tensile test in order to their failure modes and stress-strain curves. The proposed simulation method will be verified by comparing the numerical results with the test ones, in terms of temperature history curves, failure modes and stress-strain curves.

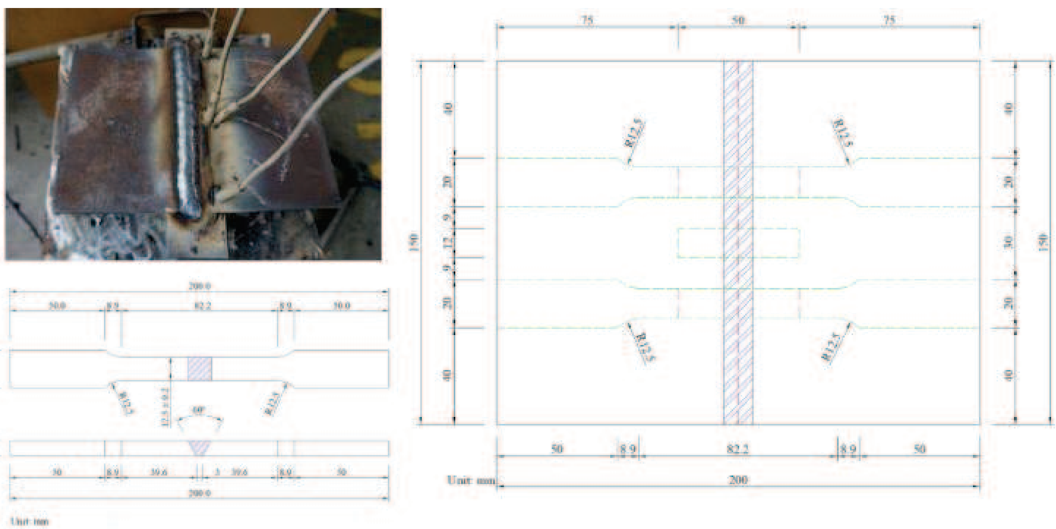


Figure 1. Geometric dimension of tested S690Q HSS butt joints

Table 1. Welding parameter of welded S690Q HSS butt joints

Joint	Electrode diameter (mm)	Voltage (V)	Current (A)	Pass number	Welding heat input per pass (kJ/mm)	$\Delta t_{8/5}$ (s)
BJ8-3.2	3.2	30	117	1	1.13	18.7
				2	1.33	
				3	1.17	
				4	1.36	
BJ8-4.0	4.0	30	125	1	1.37	39.2
				2	1.50	
				3	1.65	
				4	1.81	
BJ8-5.0	5.0	30	160	1	1.37	34.0
				2	1.54	
				3	1.62	
				4	1.43	

2.2 Material Property Definition

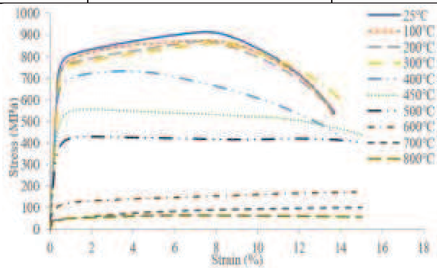
The sequentially coupled thermal-stress analysis consists of thermal analysis and stress analysis. In the thermal analysis, the whole process of the four-pass welding is reproduced. Double ellipsoid heat source is defined in subroutine DFLUX to simulate the welding heat source of shielded metal arc welding (SMAW), and the element "birth and death" technique is used to simulate the welding process. In additional, the thermal properties of S690Q HSS, including density, thermal conductivity, specific heat and latent heat, are also defined in the thermal analysis model. The density is assumed to be 7850 kg/m^3. The latent heat of HSS is defined as 300 kJ/kg with liquidus temperature 1480 ˚C and solidus temperature 1430 ˚C. The specific heat c_a and conductivity λ_a are determined according to the specifications in EC3: part 1-2 (BSI 2005). The temperature history of every node obtained by thermal analysis are input into stress analysis model to consider the welding influence on mechanical property of S690Q HSS.

In the stress analysis model, the standard tensile tests of the S690Q HSS butt joints are simulated once the temperature history of all nodes are input completely. The mechanical properties of S690Q HSS and weld material at room temperature are listed in Table 2. The temperature-and cooling rate-dependent material properties of S690Q HSS defined in stress analysis model are presented in Figure 2, including the stress-strain curves of S690Q HSS at elevated temperatures (Chiew, Zhao, Lee 2014) and the stress-strain curves of S690Q HSS cooling from different peak temperatures with different cooling rates. Furthermore, the expansion coefficient ε_T of steel is also considered in the finite element models (FEMs) according to the specified equations in EC3. Two other user subroutines USDFLD and UEXPAN are created to determine the stress-strain curve at all nodes of the model according to the highest peak temperature and the corresponding cooling rate at which the node is experienced during welding and this allows the inhomogeneous material property of the HAZ is considered in the stress analysis.

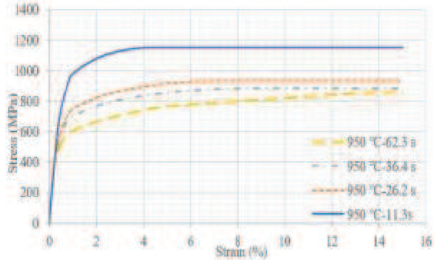
Table 2. Mechanical properties of S690 HSS and weld metal at room temperature

Material	Elastic Modulus (GPa)	Yield Strength (MPa)	Ultimate Strength (MPa)	Elongation (%)
S690Q HSS	208.9	745.2	837.8	14.5

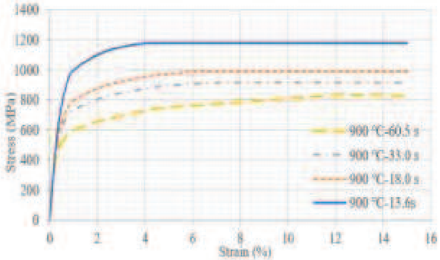
LB-80L	210.0	767.0	848.0	22.0



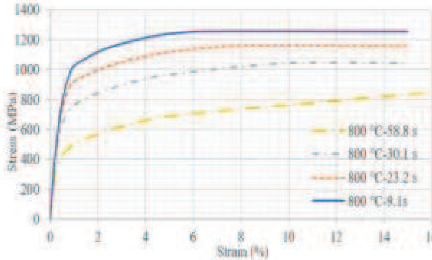
(a) Material property at elevated temperatures



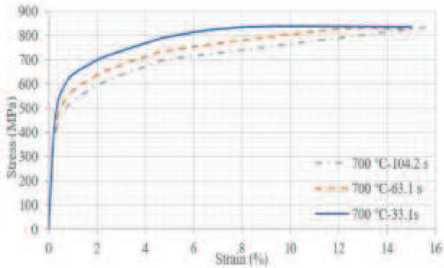
(b) Material property cooling from 950 °C



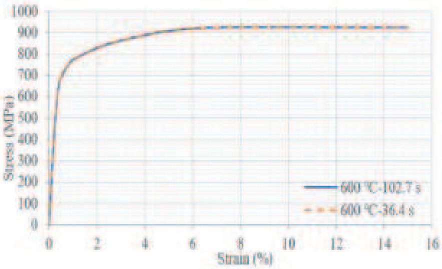
(c) Material property cooling from 900 °C



(d) Material property cooling from 800 °C



(e) Material property cooling from 700 °C

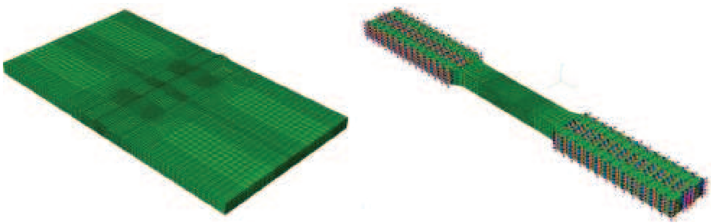


(f) Material property cooling from 600 °C

Figure 2. Material property of S690Q HSS defined in ABAQUS

2.3 Mesh and Boundary Condition

The meshes of thermal analysis model and stress analysis model are shown in Figure 3. The ambient temperature is assumed as 31°C according to the measured temperature of HSS plate before welding. The thermal boundary of butt joint is composed of convection and radiation with coefficients of 25 W/(m^2·°C) and 0.5, respectively. For the physical support boundary, the position of plate joint is fixed during welding process, but the expansion of joint caused by temperature change is not restricted. When the welding process is completed, the "birth and death" element technique is adopted to cut out the coupon for the following tensile test analysis.

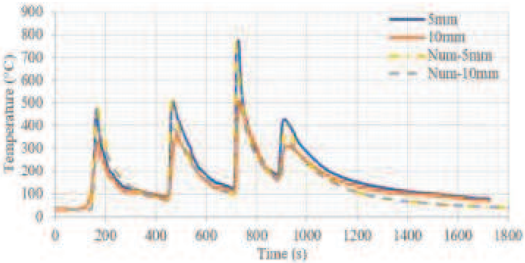


(a) Thermal analysis model (b) Stress analysis model

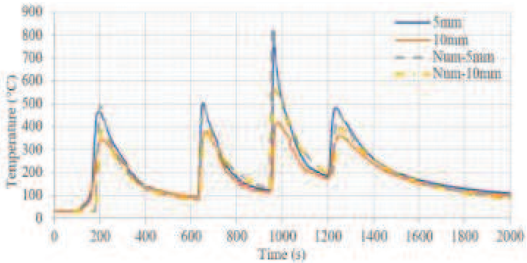
Figure 3. Numerical model of S690Q HSS butt joint

2.4 Comparison of experimental and numerical results

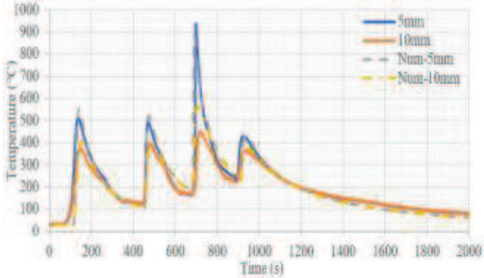
Figure 4 shows the comparison of temperature history curves obtained from tests and numerical models. The measured two points are located at the middle of butt joint with 5 mm and 10 mm away from the top bevel edge of weld, respectively. It can be seen that the temperature history curves obtained from FEMs match well with ones from tests, especially the peak temperature and cooling rate, which proves the accuracy of thermal analysis modes.



(a) BJ8-3.2



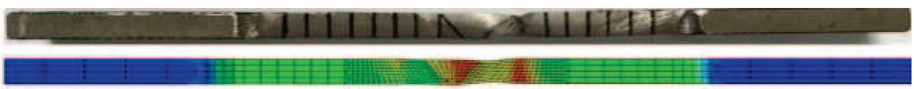
(b) BJ8-4.0



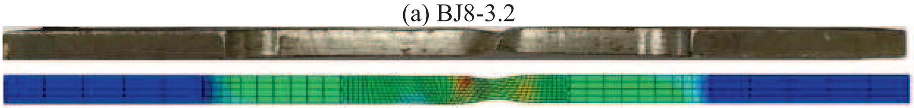
(c) BJ8-5.0

Figure 4. Comparison of temperature history curves

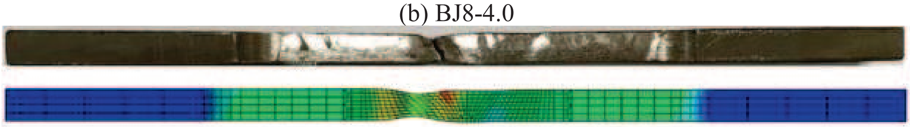
The failure modes gained from tests and FEMs were compared in Figure 5 which shows that the verification models and tested specimens have the same failure mode with fracture occurred in HAZ. That means the strength of HAZ is weaker when compared with weld and base material, Therefore, it can be concluded that proposed stress analysis model is able to reproduce the welding influence on tensile behaviour of S690Q HSS butt joints reasonably.



(a) BJ8-3.2



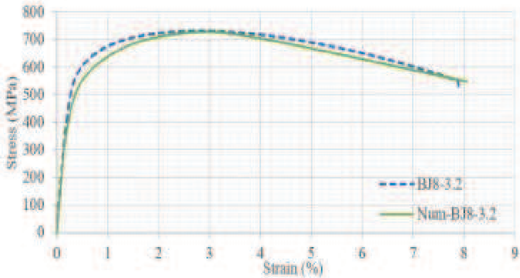
(b) BJ8-4.0



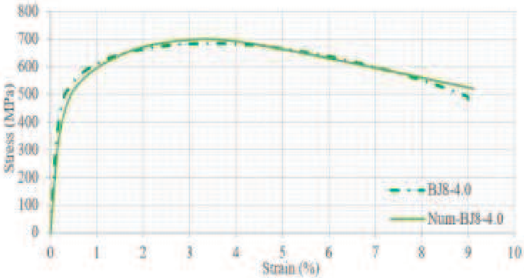
(c) BJ8-5.0

Figure 5. Comparison of failure mode

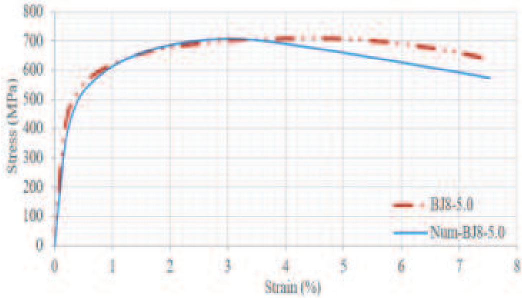
The accuracy of stress analysis mode is further verified by the comparison of stress-strain curves obtained from numerical analysis and experimental study (Figure 6). Furthermore, the mechanical properties of S690Q HSS butt joints extracted from the stress-strain curves, including elastic modulus, yield strength and ultimate tensile strength, are listed in Table 3.



(a) BJ8-3.2



(b) BJ8-4.0



(c) BJ8-5.0

Figure 6. Comparison of stress-strain curves

Table 3. Mechanical property of S690Q HSS butt joints from experimental and numerical results

Specimen	Test-E (GPa)	Num-E (GPa)	Test-f_y (MPa)	Num-f_y (MPa)	Error of f_y (%)	Test-f_u (MPa)	Num-f_u (MPa)	Error of f_u (%)
BJ8-3.2	211.2	200.3	603.4	546.1	9.5	730.6	727.9	0.4
BJ8-4.0	209.3	200.1	542.9	506.9	6.6	686.6	702.1	2.3
BJ8-5.0	207.5	199.8	544.2	520.2	4.4	708.7	706.8	0.3

It is found that the stress-strain curves obtained from numerical results agreed well with the experimental curves, although there is some difference at the beginning of plastic stage. One possible explanation for this is that only a limited numbers of sets of material property data obtained from different cooling rates were available. For example, the highest temperature considered in FEM is 950 °C, but the highest temperature in HAZ during welding almost reaches to 1350 °C. The coarse grained HAZ, which generally has higher strength than fine grained HAZ, usually goes through the peak temperature ranging from 950 °C to 1350 °C. Since there is no relative experimental data of S690Q HSS cooling from the peak temperature in this range with different cooling rates, the post welding material properties with peak temperature 950 °C are defined for this area in numerical model. It directly leads to the lower strength of HAZ compared with the true situation. In addition, the predicted ultimate tensile strength of FE model is more accurate compared with yield strength. The errors of yield strength varied from 4.4 % to 9.5 %, and the tensile strength errors were ranging from 0.3 % to 2.6 %. Therefore, it can be concluded that the proposed simulation method is capable of estimating the tensile behaviour of welded RQT S690Q HSS butt joint accurately.

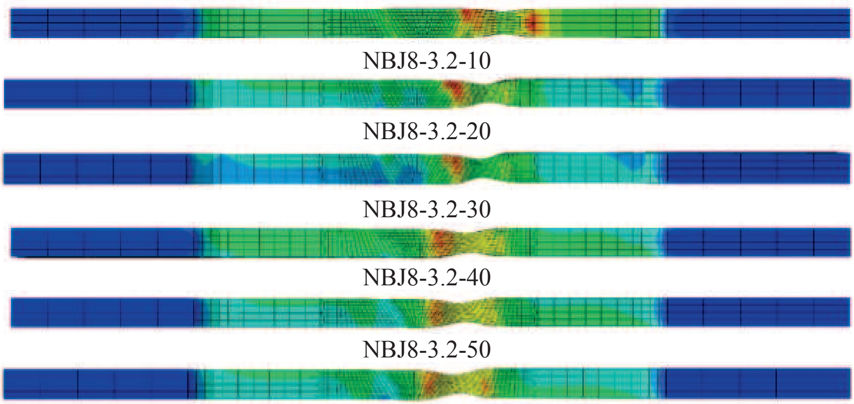
3 Parametric Study

In view of the fact that a faster cooling rate of steel generally leads to harder microstructure, a faster cooling rate is supposed to be beneficial to the post-weld mechanical performance of

S690Q HSS butt joints. Therefore, a parametric study was conducted to study the influence of cooling rate on the tensile behaviour of S690Q HSS butt joints. $\Delta t_{8/5}$, the cooling time for steel to cool from 800 ℃ to 500 ℃, is taken as the principle factor. A larger $\Delta t_{8/5}$ means slower cooling rate of welded butt joints. Table 4 listed all the numerical model employed in the parametric study. The failure modes of NBJ8-3.2 series are shown in Figure 7. It can be observed that with increase of the $\Delta t_{8/5}$, the failure position gradually moved from base material to HAZ.

Table 4. Parameters of the numerical models for parametric study

Plate thickness (mm)	Model	Average heat input (kJ/mm)	$\Delta t_{8/5}$ (s)
8	NBJ8-3.2-10	1.25	10
	NBJ8-3.2-20		20
	NBJ8-3.2-30		30
	NBJ8-3.2-40		40
	NBJ8-3.2-50		50
	NBJ8-3.2-60		60
	NBJ8-4.0-10	1.58	10
	NBJ8-4.0-20		20
	NBJ8-4.0-30		30
	NBJ8-4.0-40		40
	NBJ8-4.0-50		50
	NBJ8-4.0-60		60
	NBJ8-5.0-10	1.49	10
	NBJ8-5.0-20		20
	NBJ8-5.0-30		30
	NBJ8-5.0-40		40
	NBJ8-5.0-50		50
	NBJ8-5.0-60		60



NBJ8-3.2-10

NBJ8-3.2-20

NBJ8-3.2-30

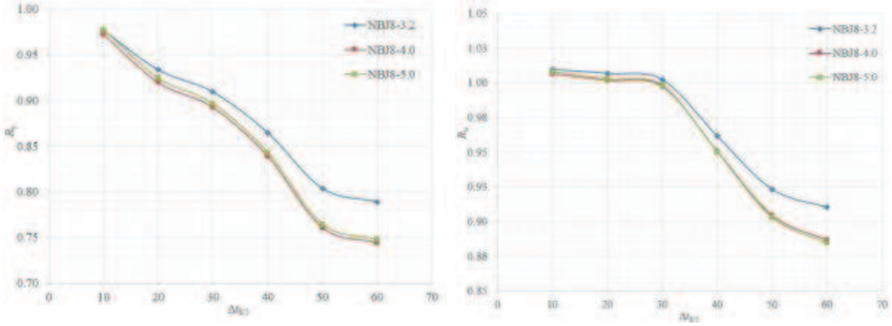
NBJ8-3.2-40

NBJ8-3.2-50

NBJ8-3.2-60

Figure 7. Failure modes of NBJ8-3.2 series

Figure 8 presents the yield strength reduction factor R_y (ratio of yield strength of butt joint to yield strength of S690Q HSS) and the tensile strength reduction factor R_u (ratio of ultimate tensile strength of butt joint to yield strength of S690Q HSS) curves obtained from the parametric study. It is observed that the strength of S690Q HSS butt joint decreased when higher welding heat input was adopted and the strength reduction factors decreased as $\Delta t_{8/5}$ increased. Therefore, it can be concluded that the tensile strength reduction of S690Q HSS butt joint can be controlled by adopting a higher cooling rate.



(a) Ry-$\Delta t_{8/5}$ curves (b) Ru-$\Delta t_{8/5}$ curves

Figure 8. Reduction factor curves of NBJ8-3.2 series

4 Conclusions

In this study, an improved numerical modelling procedure is proposed to predict the tensile strength of welded S690Q HSS butt joints. The proposed procedure considered the inhomogeneous material properties of the HAZ of the joint which is caused by non-uniform cooling rate during welding. The numerical model is validated by comparing the predicted coupon tensile strength of the joints with experimental results. It is found that the proposed simulation method was able to predict the tensile behaviour of S690Q HSS butt joints reasonably. In addition, a parametric study was conducted, and the results indicated that the strength of S690Q HSS butt joint decreases as the welding heat input increase. In addition, the strength reduction of S690Q HSS butt joint can be controlled by increasing the cooling rate of the joint.

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