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Determination of the local constitutive properties of the welded steel joints using digital image correlation method

Yang Peng [a,*], Chao Wu [b], Jieliang Gan [a,c], Jun Dong [a]

[a] College of Civil Engineering, Nanjing Tech University, 211816 Nanjing, China
[b] School of Transportation Science and Engineering, Beihang University, 100191 Beijing, China
[c] Taihu Construction Quality and Safety Supervision Station, 246430 Taihu, China

HIGHLIGHTS

- Local constitutive properties across welded joints can be obtained by DIC approach.
- All of the stress-strain curves across welded joints do not show Lüders plateau.
- The strength of the welded joints follows the sequence of WM > HAZ > BM.
- The ductility of welded joints follows the sequence of BM > WM > HAZ.

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ABSTRACT

The digital image correlation (DIC) method has become popular to characterize the local constitutive properties distribution especially for the welded joints. Although the evaluation of the local constitutive properties of a specimen is possible using DIC, few research has been reported to characterize these properties of the welded steel joints. This paper presented a method to evaluate the local constitutive properties of a welded steel joint through tensile testing and DIC method. Firstly, tensile tests of the welded steel joint were carried out and the stress-strain curves of different locations of the welded steel joint were obtained by the DIC method. Then these experimental stress-strain curves were fitted by an appropriate material model. Constitutive properties at these specific locations of the welded steel joint were then determined using this model based on test standards and the Considère criterion. The results showed that the Young's modulus of different sub-regions of the welded steel joints were almost constant. The yield and tensile strength decreased from the weld metal (WM) to the heat affected zone (HAZ) and the base metal (BM). It was also found that the hardening properties of different sub-regions of the welded steel joint followed the sequence of BM > WM > HAZ. This paper contributed a simple method to characterize the local material properties of welded steel joint.

1. Introduction

Structural steels are commonly used in engineering structures, such as power transmission towers, cranes, bridges and offshore platforms. Welding is widely used to connect the members of the steel structures due to its flexibility and rigidity. During the welding process, thermal cycling and solid-state phase transformation occur resulting in extensive microstructure variation in the welded joints. The heterogeneous microstructure could lead to inhomogeneous mechanical properties surrounding the welded regions [1–3]. Because of the non-uniform distribution of the mechanical properties, local stress concentration exists in the welded joints [1,4]. Lüders plateau is normally observed in the stress-strain curve of mild steel indicating plastic deformation. However, it is reported that the Lüders plateau disappeared for the steel in the heat affected zone of welded joints [5,6]. Because the mechanical properties of steel are different at different sub-regions, non-uniform plastic deformation would occur in the welded joints. The local stress concentration and the non-uniform plastic deformation would greatly affect the mechanical behavior of the welded joints, such as lowering the fatigue strength and reducing the ductility [7–11]. Therefore, it is very important to develop a method which is able to comprehensively describe the local constitutive

* Corresponding author.
E-mail addresses: yang.peng@njtech.edu.cn (Y. Peng), wuchao@buaa.edu.cn (C. Wu), 534529149@njtech.edu.cn (J. Gan), dongjun@njtech.edu.cn (J. Dong).

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Table 1
Chemical compositions of the Q345 steel and the F5A2-10Mn2 filler metal (weight percentage).

Materials	C	Si	Mn	P	S	Ni	Cu	Cr
Q345	0.14	0.41	1.46	0.013	0.009	0.005	0.004	0.021
F5A2-10Mn2	0.082	0.04	1.59	0.011	0.006	0.012	0.033	0.047

properties of the welded steel joints, such as stress-strain curve, elastic modulus, yield strength, tensile strength, and etc.

Many studies have been carried out to characterize the local constitutive properties of the welded joints. One convenient method is to characterize the steel strength of the welded joints by measuring the material hardness. Various functions have been proposed [12–14] to convert the hardness data to strength data, and experimental standard with such converting function has also been developed by the International Organization for Standardization [15]. Though convenient to apply, the proposed functions were empirical by fitting experimental results in their specific tests. General applicability of these functions has not been validated yet. In addition, only local mechanical properties can be obtained using these functions, while the whole constitutive stress-strain relationship of the sub-regions of the welded joints cannot be achieved. Another method is to use thermal simulation, which reproduces the specific microstructure of the sub-regions of the welded joints based on the recorded thermal history [16–18]. The local constitutive relationship can be obtained by thermal measurement of the specimen. However, the transient thermal gradients of the welded steel joints are hard to measure, and the accuracy is low with high cost. The local mechanical properties of the welded steel joints can also be obtained by cutting micro-specimens and conducting tensile, shear and punch tests [6,19–22]. Though the local constitutive relationship can be directly obtained, it requires manufacturing micro-size specimens which are complicated, expensive and time consuming. The loading-unloading curves obtained from the indentation test were used to determine the local constitutive relationship of the sub-regions of the welded steel joints [1,22,23]. The indentation method is a non-destructive method. However, empirical formulae or the inverse analysis of this method need sufficient experimental verification.

Digital image correlation (DIC) can be a promising method for the rapid determination of the mechanical behavior and constitutive properties of the different sub-regions the weld steel joints. However, there is limited research using DIC for such characterization of welded joints. Reynolds and Duvall [24] proposed a uniform stress method to quantify the local stress-strain relationship using DIC. It was assumed that the stress in every cross section of the welded joints was uniform which was equal to the force divided by the cross section area. The local strain values were measured by DIC, so that the local constitutive properties of the sub-regions of the welded joints were determined based on the local stress and strain. This uniform stress method has been widely used to study different types of welded joints in [25–29]. However, Lockwood et al. [30] investigated the reliability of this uniform stress assumption by conducting FE simulation. It was found that the FE results and results from the uniform stress method did not agree well. Sutton et al. [31] proposed a virtual field method to determine the local constitutive properties of the welded joints. The local strain fields were obtained using DIC. Several researchers compared the virtual field method with the uniform stress method [31–33], and found that the two methods had the same accuracy. However, the virtual field method assumed the mechanical properties were constant in the sub-regions. Leitão et al. [34] considered the local stress concentration in the welded joints due to the non-uniform distribution of the mechanical properties. They proposed a method based on the volume preservation assumption to calculate the cross-section variations due to the local stress concentration. This method was called non-uniform stress method which has been successfully used to assess the local constitutive properties of friction stir welds and gas tungsten arc welds [4,34–37]. However, the non-uniform stress method focused on the materials with homogenous plastic response. It cannot be applied to materials with Lüders plateau in their constitutive relationship such as structural steel.

Table 2
Mechanical properties of the Q345 steel and the F5A2-10Mn2 filler metal.

Materials	Yield strength σ_y (MPa)	Tensile strength σ_t (MPa)	Elongation δ (%)
Q345	≥335	470–630	≥20
F5A2-10Mn2	≥400	480–650	≥22

Table 3
Welding parameters.

Arc energy (kJ/cm)	Amps. (A)	Volts (V)	Travel speed (cm/min)
18.2–21.4	560–590	26–29	48.0
18.8–27.4	550–635	25–29	40.0–46.0
28.4–28.4	630–650	30–35	47.0–48.0

This paper aims to improve the non-uniform stress method and use it to study the local constitutive properties of the structural steel welded steel joints. For this purpose, two single V groove butt welded Q345 steel joints were prepared using metal arc welding. Tensile tests were conducted on these two welded steel joints. The local strain was measured using DIC. Finally, the local constitutive properties across the welded steel joints were determined by the non-uniform stress method.

2. Experimental program

2.1. Materials and welding parameters

Q345 steel plate of 20 mm thick was selected for the welded steel joints. The automatic submerged arc welding (SAW) with an electrode F5A2-10Mn2 was used for the single V groove butt welding. The chemical compositions in weight percentage of the Q345 and the filler metal are listed in Table 1. The mechanical properties of the Q345 and the filler metal are presented in Table 2. The SAW welding parameters are given in Table 3.

2.2. Tensile testing on the welded steel joints

Two tensile specimens were cut from the welded steel plates (Fig. 1) with the welding located in the middle of the specimens. The specimens had a cross-section of 25 mm × 20 mm, and the gauge length was 100 mm (Fig. 1). The loading

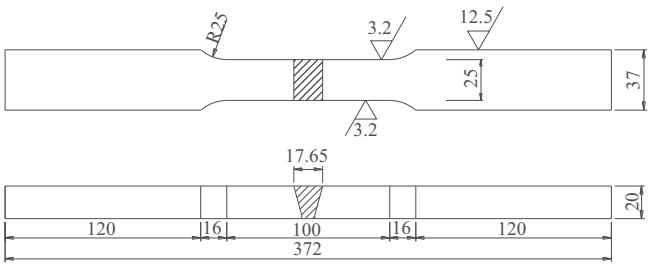

Fig. 1. Tensile specimen of the welded steel joints (dimensions in mm).