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Investigation of residual stresses in Q460GJ steel plates from medium-walled box sections

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ABSTRACT

Residual stress is an important factor that can have considerable effect on the behaviour of steel structures. In the past, most of the research has been focused on determining the residual stress in members consisting of traditional normal strength and high strength steels. There has been little research on residual stresses in members fabricated from high performance steels such as GJ steel. The work detailed in this paper aims to experimentally investigate the residual stresses in welded box sections fabricated from Q460GJ high performance structural steel plates. A total of eight full-scale welded box sections, with nominal wall thicknesses of 12 mm and 25 mm, were tested using the sectioning method. Both the circular curve correction method and the straightening measurement method were used in this study to obtain the magnitude and distribution of the longitudinal residual stresses. In addition, the effects of steel plate thickness and the plate width-to-thickness ratio on the residual stress were investigated. A simplified residual stress distribution model, which would be of great assistance in investigating the buckling behaviour of GJ-type steel members, is proposed based on the experimental results.

1. Introduction

GJ steel, which was developed in China, is a new type of high performance steel (HPS). Compared with conventional steels, such as normal strength steel (NSS) and high strength steel (HSS), the impact toughness, lamellar tearing resistances, and weldability have been greatly improved in GJ steel. Practical applications of GJ steel can be found in many landmark structures in China, including the National Olympic Stadium (Birds Nest) and the new CCTV Headquarters [1]. Noting that residual stress, which inevitably arises in steel members, has an adverse effect on the structural behaviour, extensive research on residual stress in NSS and HSS materials has been conducted to examine its distribution and effect.

The study of residual stress in NSS can be dated back to research in 1888, in which Kalakoutsky proposed the sectioning method to measure the sectional residual stress [2]. In 1934, the hole-drilling strain method was put forward by Josef to measure the residual stress in steel members [3]. In 1936, Gisen and Gloker developed a non-destructive test method using X-ray stress analysis to investigate the residual stress [4]. Alpsten and Tall [5] adopted the sectioning method to test the residual stresses of H-shaped sections as they varied with different welding methods, plate thicknesses, and other influencing factors. Tebedge [6] employed the sectioning method and the hole-drilling method to study the residual stresses in welded H-shaped sections. Wang [7] conducted an investigation on the residual stresses in welded H-shaped sections and rolled I-shaped sections using the sectioning method, the hole-drilling method, and the X-ray method. Simplified residual distribution models have also been proposed based on the experimental results in that study.

In addition to the work on NSS, in-depth research on HSS has also been performed. Rasmussen and Hancock [8, 9] examined the residual stresses of welded-section specimens fabricated from 690 MPa steel plates using the sectioning method. Two different steel plate thicknesses with three different section types (box, cruciform, and I-shaped), were considered in this research. Wang [10, 11] measured the residual stresses in box and H-shaped sections fabricated from Q460 MPa steel plates using both the sectioning method and the hole drilling method. Ban [12–14] tested the residual stresses of welded box and I-shaped sections for a maximum steel plate thickness of 14 mm and a maximum yield strength of 960 MPa using the sectioning method.

Compared with the research works on NSS and HSS, existing research on the residual stress in HPS members is scant. Nishino [15] measured the residual stresses in a total of eight specimens fabricated from A7 and A514 steel using the sectioning method and summarised the pattern of residual stresses. Spoorenberg [16] carried out an experimental program on two heavy-quenched and self-tempered sections with a flange thickness greater than 100 mm. Yang [17] performed an experimental investigation on the residual stresses in eight full-scale I-shaped sections welded from flame-cut Q460GJ steel plates. However, this

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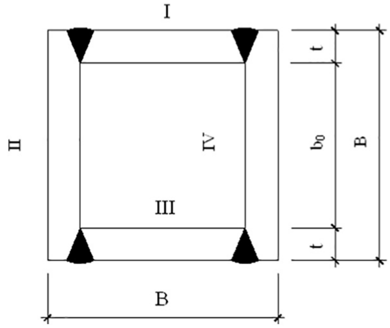

Fig. 1. Sectional dimension schematic.

Table 1
Nominal dimensions of the experimental specimens.

Specimens	BR1	BR2	BR3	BR4	BR5	BR6	BR7	BR8
B (mm)	120	168	216	264	175	200	225	250
t (mm)	12	12	12	12	25	25	25	25
b_0/t	8	12	16	20	5	6	7	8

Note: B and t are the width and thickness of the wall. b_0/t is the width-to-thickness ratio of the wall, in which b_0 = B-2 t.

study of HPS materials only addressed I-shaped sections. To the authors' knowledge, [15] is the only research that focuses on the residual stresses in an HPS box section. Unfortunately, the bending correction of the sectioning method is not considered in that study and no residual distribution model is proposed. The existing research on residual stresses in HPS are primarily aimed towards the investigation of residual stresses in steel members fabricated from thin plates; research on residual stresses in medium-thickness plates, which are defined to be the plates with a thickness within the range of 12 mm to 25 mm in this study, has not yet been undertaken.

As an extension of previous research [17–19], this current work aims to investigate the residual stress in welded medium-walled box sections fabricated from Q460GJ structural steel plates using the sectioning method. The measured strip bending is corrected in this study using the curve correction method and the straightening measurement method. A simplified residual stress distribution model is then proposed based on the experimental results from the sectioning of the eight box sections.

2. Experimental program

2.1. Experimental specimens

As mentioned above, a total of eight box sectional members (schematic shown in Fig. 1) were tested in this study. In Fig. 1, B and t denote the width and thickness of the wall, respectively. In this study, all the specimens were welded from flame-cut plates with nominal thicknesses of either 12 mm or 25 mm. Hereinafter, the plates of the section are numbered from "I" to "IV". Plates I and III represent the ones which the welds located in, plates II and IV are the others. Note that the residual stresses in Plates I and III are inherently different from those in Plates II and IV owing to the configuration of the welds. In addition, it should also be noted that the welding sequence is a key factor affecting the residual stresses. In this current study, Plates I was welded to Plates II and IV before Plates III according to two simultaneously formed weld seams. In other words, the two weld seams on Plate I were formed simultaneously before those two on Plate III.

Table 3
Material properties.

Thickness of steel plate t (mm)	Elastic modulus E (GPa)	Yield strength f_y (MPa)	Ultimate tensile strength f_u (MPa)
12	209	571	678
25	211	485	628
25	208	424	563

To investigate the residual stress in the welded box section specimens systematically, the width-to-thickness ratio of the plates in the experimental specimens was varied from 5 to 20. The nominal dimensions of all the eight specimens are summarised in Table 1.

It is worth pointing out that the material processing technology, including the welding and cutting methods, could affect the magnitudes and distributions of residual stresses in the specimens. Hence, the relevant parameters during the welding and cutting stages were recorded. CO_2 gas-shielded welding was used for specimens with 12 mm steel plates and submerged arc welding was used for specimens with 25 mm steel plates. More details about the welding methods used are summarised in Table 2.

2.2. Material properties

The tensile coupon tests were performed in accordance with GB/T GB2975–1998 [20] and GB/T 228.1-2010 [21]. A SANS electronic universal testing machine with an accuracy of ±1% was used to carry out this test. A stress controlled loading at a rate of 10 MPa/s was used in the elastic stage, while a strain control loading at a rate of 0.001/s was adopted in the post-yield stage. Displacement control loading was adopted in the strengthening stage at a rate of 10 mm/min. Strain gauges, which were used to capture the initial component of the stress-strain curve, were attached to both sides of the specimens. The remainder of the stress-strain curve was obtained using an extensometer. The obtained material properties, including the elastic modulus, yield strength, ultimate tensile strength, are listed in Table 3. To determine these properties, three tensile tests were conducted for each thickness of plate. It should be noted that two different 25 mm thick steel plates were used to fabricate the members in this study. Thus, there are two different sets of material results for the 25 mm nominal thickness steel plate (see Table 3). One of the 25 mm steel plates was found to have yield strength of 424 MPa, which is lower than the specified nominal yield strength of Q460GJ steel. Several repeated tensile coupon tests were conducted by the authors on this plate and similar results were obtained each time. Thus, the low yield strength observed in this plate may be a result of a manufacturing defect.

2.3. Experimental procedure

As mentioned above, the sectioning method was employed to investigate the residual stress in the fabricated specimens (see Fig. 2). The basic principle of the sectioning method is to determine the residual

Table 2
Welding parameters.

Procedure	Voltage (v)	Current (amp)	Speed (mm/s)	Preheatingtemperature (°C)	Interpass temperature (°C)	Holding temperature (°C)	Holding time(h)
Backing Welding	19–23	92–103	9.1	100–150	150–180	200	1
BR1-BR4	21–23	114–120	8.1	100–150	150–160	165	1
BR5-BR8	31–35	600–680	4.2	150	150–160/160–190/180–250/260–300/350	200	1