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Experimental and model investigation on residual stresses in Q460GJ thick-walled I-shaped sections

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ABSTRACT

Residual stresses can occur through a variety of mechanisms, and welding is one of mechanisms. This kind of stress variation through materials can be very complex and can vary between compressive and tensile stresses from layer to layer. A new type of high performance structural steel named by Q460GJ has been increasingly utilized in many large scale steel constructions in China, such as the National Stadium of China in Beijing (Birds Nest) and Canton Tower in Guangzhou. Q460GJ structural steel has a nominal yield strength of 460 MPa, which does not decrease significantly with the increase of steel plate thickness. Thus, Q460GJ structural steel is normally used in thick-walled welded sections. Nevertheless, the residual stresses on thick-walled sections may be more complex. Currently, only limited knowledge is available on the residual stress distribution of the members fabricated from high performance structural steel plates, especially for thick-walled sections. In this paper, the residual stresses in four welded medium-walled and four thick-walled H-section specimens fabricated from Q460GJ structural steel plates were studied by experimental tests. Residual stresses were measured by sectioning method, and the variation of residual stress through plate thickness was determined by slicing method. This study provides the magnitude and distribution of the longitudinal residual stresses. This paper also explores the effect of plate thickness on residual stress distribution and the interaction between flanges and webs. Finally, based on the statistical evaluation of the experimental results, a simplified multilayer residual stress model is proposed for predicting residual stress.

1. Introduction

High Performance Steel (HPS) structures have all the advantages of mild steel structures, such as good plasticity and toughness, as well as short field construction time due to the suitability for workshop prefabrication. Beside, HPS structures could sustain higher loading and have smaller member sizes, which means lighter self-weight and faster construction time. Moreover, the effect of residual stress of HPS structural members is not as significant as that of mild steel. Thus, HPS structural members have higher buckling resistances. The advantages of HPS have stimulated a great interest in developing HPS for the wide usage in building and bridge constructions. In China, a new type of HPS, named by Q460GJ structural steel has been developed. Q460GJ structural steel has been increasingly adopted in many well-known large scale steel structures, like National Olympic Stadium (Birds Nest), Canton Tower, Goldin No.117 Financial Center (under construction) and Hanking Financial Center (under construction). Q460GJ structural steel has a nominal yield strength of 460 MPa and the yield strength of Q460GJ structural steel does not decrease with the increase of steel plate thickness. Thus, Q460GJ structural steel is generally used in heavy sections of large scale structural projects. Fig. 1 indicates the decline of nominal yield strength of Q460GJ [1] and S460 [2] structural steel with the increase of material plate thickness. From the figure, it can be found that when the thickness is in the range of 0 to 16 mm, the nominal yield strength of both Q460GJ and S460 structural steel is 460 MPa. However, when the steel plate thickness is in the range of 25 mm to 42 mm, the nominal yield strength of Q460GJ structural steel is 5% higher than S460 structural steel. When the thickness increases to be 80 mm, the nominal yield strength of Q460GJ structural steel is 7% higher than S460 structural steel. Due to the low thickness effect on yield strength, Q460GJ structural steel shows greater advantages in thick-walled sections of heavy construction projects. Recently, the authors' research group in Chongqing University in China has conducted a series of studies on Q460GJ structural steel by experimental tests, mainly including material properties, residual stresses in welded sections and the mechanical performance of structural members. Yang et al. [3] investigated the residual stresses on eight full scale

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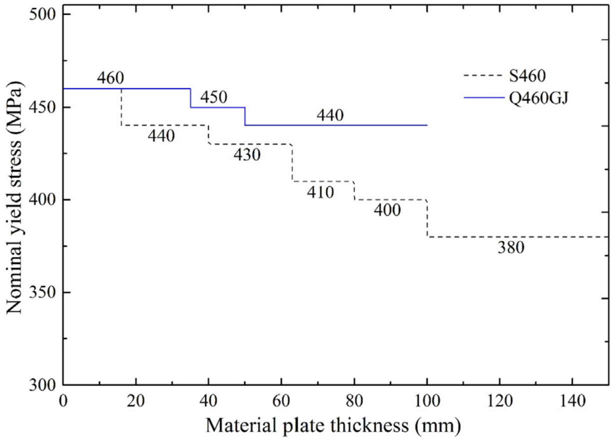

Fig. 1. Nominal yield stress variations with the material plate thickness of Q460GJ and S460 structural steel.

H-sections welded by flame-cut Q460GJ steel plates, including five doubly symmetric sections and three singly symmetric sections. Also, a total of eight doubly symmetric welded section beams and six singly symmetric I-shaped beams were tested under a concentrated force at mid-span to investigate the global stability behavior of Q460GJ structural steel beams. And the test and numerical results have been compared with the buckling strengths calculated by China, America and Europe design codes [4,5].However, all the studies on Q460GJ structural steel, which aimed to a high depth-width ratio and thin plate I-shaped section is usually used as beams, only cover the sections with less than 20 mm thick section walls. Nevertheless, Q460GJ structural steel has the advantages to be applied in thick-walled sections, as discussed above. Thus, more studies on Q460GJ structural steel, which aimed to the section of smaller depth-width ratio and thicker plate is usually used as columns, are needed, especially on the structural behavior of thick-walled sections.

The manufacturing processes, such as flame-cutting, hot-rolling and welding, can result in significant residual stresses. Heat from welding may cause localized expansion, which is taken up during welding by either the molten metal or the placement of parts being welded. When the finished weldment cools, some areas cool and contract more than others, leaving residual stresses. The existence of residual stress could decrease the stability carrying capacity. Seemingly important as the residual stress is, it is difficult to be predicted by theoretical analyses. Therefore, measured residual stresses are normally preferred to obtain the distribution and magnitude of residual stresses. For Normal Strength Steel (NSS), in the 20th century, there were a lot of research studies about residual stress [6–16]. The residual stress distributions for different shape sections and different manufacturing processes were extensively studied and the conclusions have been adopted in many national codes [17–19]. Nevertheless, the residual stress model proposed for NSS may not be applicable for HSS. From last century to now, some studies [20–25] were performed for structural members fabricated from HSS plates with 460–800 MPa yield strength. More details of those studies can be found in Table 1. In these residual stress studies, Rasmussen and Hancock [20,21] considered four types of cross sections with 690 MPa nominal yield strength and two different manufacturing processes, namely shear cutting and flame cutting. Beg and Hladnik [22] examined two sections with shear cutting. Dae-Kyung Kim [23] tested two specimens fabricated by the thermo-mechanical control process without the costs of quenching, tempering, and alloying. The measured magnitude and distribution of residual stresses were further applied in column buckling analyses. Three welded 460 MPa I-shaped sections were tested by sectioning method and hole drilling method by Wang et al. [24]. Ban et al. [25] investigated seven sections of various sizes with fillet welds and one section fabricated through butt and fillet combined welds. As shown in Table 1, all of those residual stress tests involved plate thickness ranging from 6 mm to 21 mm, which do not cover thick-walled sections. Dwight and his associates at Cambridge [26] have done much work on NSS sections fabricated by welding, on correlating welding parameters to residual stresses. Quayyum et al. [27] simulated the initial residual stresses in hot-rolled wide-flange shapes through computational technique to study the influence of residual stresses on structural performance. Alpsten and Tall [6] presented the residual stress measurement on heavy rolled shape sections with NSS. Spoorenberg [28] carried out an experiment program on two heavy quenched and self-tempered sections with section flange thickness greater than 100 mm. It can be found from literature review that the available knowledge about residual stresses on heavy welded I-shape sections is still limited, especially for HSS welded sections. No literature about the residual stresses on welded heavy sections fabricated from Q460GJ structural steel plates can be found. In HSS heavy sections, the distribution of residual stress may be quite complicated. Up to now, in the welded thick-walled sections fabricated from Q460GJ structural steel plates, the residual stress distribution is still not clear.

Table 1
Summary of the residual stress tests on high strength steel welded I-shaped sections.

Specimen	H (mm)	B (mm)	t_w (mm)	t_f (mm)	b_0/t_f	h_0/t_w	Nominal yield strength (MPa)
I1RS [20]	132	96	6	6	7.5	20.0	690
I2RS [20]	162	116	6	6	9.2	25.0	690
I3RS [20]	192	136	6	6	10.8	30.0	690
ISC [21]	156	140	8	8	8.3	17.5	690
Group B [22]	242	220	10	12	8.8	21.8	700
Group D [22]	242	270	10	12	10.8	21.8	700
HS-H1–310-NC [23]	310	220	15	15	6.8	18.7	800
SM-H1–370-NC [23]	370	200	15	15	6.2	22.7	490
R-H-3 [24]	168.00	156.00	11.49	21.39	3.4	10.9	460
R-H-5 [24]	243.75	225.25	11.33	21.23	5.0	17.8	460
R-H-7 [24]	319.50	314.00	11.63	21.20	7.1	23.8	460
RI1–460 [25]	110	130	10	10	6.0	9.0	460
RI2–460 [25]	150	150	10	10	7.0	13.0	460
RI3–460 [25]	210	210	14	14	7.0	13.0	460
RI4–460 [25]	150	290	10	10	14.0	13.0	460
RI5–460 [25]	276	348	12	12	14.0	21.0	460
RI6–460 [25]	300	220	12	10	10.4	23.3	460
RI7–460 [25]	360	280	12	10	13.4	28.3	460
RI8–460 [25]	150	150	10	10	7.0	13.0	460

This paper presents an experimental investigation on the residual stresses in four welded medium-walled and four thick-walled I-shaped sections fabricated from Q460GJ structural steel plates by sectioning method. And based on the statistical evaluation of the experimental results, a simplified multilayer residual stress model is also proposed for further research on structural behavior.

Table 2
Specimen geometric dimensions.

Specimen	Dimension	L (mm)	H (mm)	B (mm)	t_w (mm)	t_f (mm)	b_f/t_f	h_w/t_w
H1	314×312×12×25	1642	314	312	12	25	6	22
H2	266×262×12×25	1498	266	262	12	25	5	18
H3	218×212×12×25	1354	218	212	12	25	4	14
H4	170×162×12×25	1210	170	162	12	25	3	10
H5	284×277×25×42	1552	284	277	25	42	3	8
H6	259×235×25×42	1477	259	235	25	42	2.5	7
H7	234×214×25×42	1402	234	214	25	42	2.25	6
H8	209×193×25×42	1327	209	193	25	42	2	5