Engineering Structures 165 (2018) 396–411

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Experimental and numerical investigation into temperature histories and residual stress distributions of high strength steel S690 welded H-sections

Xiao Liu, Kwok-Fai Chung*

Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hong Kong Special Administrative Region

Chinese National Engineering Research Centre for Steel Construction (Hong Kong Branch), The Hong Kong Polytechnic University, Hong Kong Special Administrative Region

A R T I C L E I N F O

Keywords:
High strength steel
Welded H-sections
Temperature measurements
Residual stress distributions
Hole-drilling method
Thermomechanical coupled analysis

A B S T R A C T

In order to exploit full structural benefits offered by high strength steel materials in construction, it is important to examine and quantify effects of welding on these steel materials for development of effective structural design. A systematic experimental and numerical investigation into thermal and mechanical responses in four S690 welded steel H-sections with different cross-sectional dimensions during and after welding was conducted.

During welding, surface temperatures of the welded sections at specific locations in close vicinity of welding lines were measured continuously using thermocouples. After welding, surface residual stresses in these welded sections were measured using an established hole-drilling method. Based on codified data and measured temperatures, three-dimensional finite element models with thermomechanical coupled analyses were established to simulate heat transfer from a welding arc onto the welded sections. After a careful calibration of predicted surface temperature histories of these sections against measured data, both through-thickness temperature and residual stress distributions of these sections were obtained. Predicted and measured surface residual stresses at specific locations of these sections were found to be in a good agreement. Hence, accuracy of the proposed models in predicting temperature histories and residual stress distributions of these welded sections are established. Averaged through-thickness residual stresses are provided as representative residual stress patterns for these sections. It should be noted that the maximum residual stresses in these welded sections are proportionally smaller than those in S355 welded sections.

Consequently, the proposed finite element models are demonstrated to be able to predict accurate temperature histories and residual stress distributions of S690 welded H-sections through thermomechanical coupled analyses. The proposed models will be readily employed to investigate welding-induced residual stresses in welded H-sections and I-sections of various steel grades and plate thicknesses with different welding parameters. Predicted residual stress patterns will then be employed for numerical investigation into (i) axial buckling behavior of slender columns made of S690 welded H-sections, and (ii) lateral torsional buckling of unrestrained beams made of S690 welded I-sections. These numerical investigations will be reported separately.

1. Introduction

For decades, common structural steel materials with yield strengths ranging from 235 to 355 N/mm^2, i.e. S235 to S355 steel materials, have been used widely in construction of buildings, bridges and heavily loaded structures owing to their excellent and consistent mechanical properties. In the past twenty years, high strength S690 to S960 steel materials become available in many parts of the world, and they offer attractive structural solutions in reducing self-weights of multi-storey buildings and long span bridges [7,33].

Welding is generally considered to be a highly effective means of connecting steel plates and sections together to form a structure. During fabrication of steel structures, welding-induced residual stresses are always present in welded sections due to highly non-uniform temperature distributions followed by different cooling rates in various parts of the steel sections [31,32,25]. Although section resistances of these welded sections are unlikely to be reduced, residual stresses have an adverse effect on stiffness, and hence, stability of these welded sections.

In the past decades, many researchers conducted experimental investigations into residual stress patterns of S235 to S355 welded sections. A simplified residual stress pattern for S235 to S355 welded

* Corresponding author at: Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hong Kong Special Administrative Region.
E-mail address: cekchung@polyu.edu.hk (K.-F. Chung).

https://doi.org/10.1016/j.engstruct.2018.03.044
Received 15 December 2017; Received in revised form 13 March 2018; Accepted 16 March 2018
Available online 30 March 2018

sections was recommended by an ECCS document [16], and it has been widely adopted in many structural steel design codes [10,11]. For S460 steel materials, Wang et al. [34] conducted a series of residual stress measurements on three welded H-sections of different cross-sectional dimensions using both 11.5 and 21.5 mm thick steel plates; all these plates were flame-cut (FC). Ban et al. [8] fabricated a total of eight H-sections made of S460 flame-cut steel plates, and cross-sectional residual stress distributions were measured using a conventional sectioning method. The residual stress patterns of these sections were found to be similar in shape, but significantly smaller, when compared with those corresponding residual stresses in the ECCS pattern. Hence, the ECCS pattern is generally considered to be rather conservative for S460 welded H-sections.

A number of studies have been conducted to investigate the residual stress patterns for high strength steel welded sections. Rasmussen and Hancock [27,28] measured compressive residual stresses in six welded H-sections made of universal-mill (UM) and flame-cut (FC) thick steel plates using the sectioning method; yield strengths of these steel plates were found to range from 660 to 705 N/mm^2. It was found that for welded H-sections with UM steel plates, compressive residual stresses at both flanges and webs of these sections decreased as their cross-sectional dimensions increased. However, for welded H-sections with FC steel plates, tensile residual stresses were found at flange tips of those sections. It is found that accuracy of maximum residual stresses measured in a flange of these sections was somehow uncertain as out of only four to five measurements in a whole flange, only one to two measurements were made near the flange/web junction where maximum stresses were expected to take place.

Recently, Lee et al. [20] investigated residual stress distributions near weld toes of a number of S690 welded T- and Y-joints through the use of a hole-drilling method according to ASTM E837 [5]. Li et al. [22] measured residual stress distributions of three S690 welded H-sections with 16 mm thick FC plates while their overall cross-sectional dimensions were found to range from 200 to 250 mm. When compared with the ECCS pattern for S235 to S355 welded steel sections, both tensile and compressive residual stress ratios at the flanges and the webs were found to be significantly smaller in magnitude. These sections were fabricated with gas metal arc welding (GMAW) with 2 number of passes per weld legs. It was concluded that the ECCS pattern was very conservative for S690 welded sections.

For numerical investigation, three dimensional finite element modelling according to computational welding mechanics [6,19] was widely adopted to simulate welding of steel sections. Thermo-mechanical coupled analysis on finite element models were employed to simulate welding-induced thermal and mechanical responses of steel sections during welding as well as after welding. For computation of heat transfer during welding, a double ellipsoidal model proposed by Goldak et al. [17] was widely adopted as an effective heat source model to simulate a welding arc. Through this heat source model, the heat energy was distributed into a double ellipsoid with two different semi-axis values in the front and the rear hemispheres. For computation of welding-induced residual stresses, various thermal properties such as thermal conductivity, specific heat capacity, and thermal expansion coefficient of steel materials at elevated temperatures were adopted. Three dimensional finite element models were generally required to obtain both temperatures and residual stresses with a certain level of accuracy though they were very time-consuming [15,18,21,29].

In general, many researchers examined residual stresses and their effects on welded sections made of steel plates with yield strengths up to 460 N/mm^2 while only limited information on residual stresses in S690 welded sections is available so far. Hence, it is necessary to investigate thermal and mechanical responses of S690 welded sections during and after welding, and to quantify both magnitudes and distributions of residual stresses.

1.1. *Objectives and scope of work*

In order to exploit full structural benefits offered by high strength steel materials in construction, it is important to examine and quantify effects of welding on these steel materials for development of effective structural design. A systematic experimental and numerical investigation into thermal and mechanical responses in S690 welded steel H-sections was undertaken, and the investigation took the following forms of activities:

Task A Experimental investigation

- Task A1

High strength S690 steel plates of three different thicknesses were employed to fabricate four welded H-sections of different cross-sectional dimensions.

- Task A2

During welding, surface temperature histories of these four welded H-sections at specific locations in close vicinity of flange/web junctions were measured continuously using thermocouples.

- Task A3

After welding, surface residual stresses in these four welded H-sections were measured using the hole-drilling method according to ASTM E837 [5].Task B Numerical investigation

- Task B1

Based on codified data given in EN 1993-1-2, three-dimensional finite element models with thermomechanical coupled analyses for these four welded H-sections were established using ABAQUS [3] to (i) simulate heat transfer from a welding arc onto the flange/web junctions during welding, and (ii) predict mechanical responses due to differential expansion and contraction within the welded sections after welding.

- Task B2

Comparison between measured and predicted surface residual stresses of these four welded H-sections was carried out, and averaged through-thickness residual stresses for these sections were provided.

The areas of interest of the present investigation are:

- through-thickness variations in temperatures as well as residual stresses in vicinity of flange/web junctions;
- equilibrium of forces based on welding-induced residual stresses developed over cross-sectional areas of the flange and the web in a flange/web junction; and
- representative residual stress patterns for welded H-sections.

2. Experimental investigation

2.1. *Test programme*

A total of four S690 welded H-sections with different cross-sectional dimensions, namely, Sections C1 to C4 were tested. These sections were fabricated with S690 steel plates of three different thicknesses, i.e. 6, 10 and 16 mm using two different welding methods, namely (i) Gas metal arc welding (GMAW), and (ii) Submerged arc welding (SAW). Table 1 summarizes the test programme of the experimental investigation while cross-sectional dimensions of these sections are shown in Fig. 1.