Journal of Constructional Steel Research 114 (2015) 405–416

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Hardness and compressive capacity of longitudinally welded very high strength steel tubes

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ARTICLE INFO

Article history:
Received 24 June 2015
Received in revised form 9 September 2015
Accepted 11 September 2015
Available online 16 September 2015

Keywords:
Very high strength steel tubes
Heat affected zone
Hardness
Compression capacity

ABSTRACT

This paper presents a study on the hardness and compressive capacity of longitudinally welded very high strength (VHS) steel tubes. VHS tubes, with a nominal yield stress of 1350 MPa and an ultimate tensile strength of 1500 MPa, were welded longitudinally to Grade 300 steel plates using the GTAW welding method. The hardness in the heat affected zone (HAZ) dropped to around 40% of that of the VHS steel without welding. The lowest hardness occurred at a location of about 4 mm from the weld toe. The strength in HAZ of longitudinally welded VHS tubes is about 55% of that of VHS tubes. The newly derived HAZ strength reduction factor is applied to predict the load carrying capacity of VHS tubes longitudinally welded to plates, fabricated sections with VHS tubes as corners and concrete-filled fabricated sections.

1. Introduction

The research on high strength and ultra-high strength steel has gained extensive interests of many researchers [1–6]. The very high strength (VHS®) circular steel tube used in this study is a quenched and tempered thin walled hollow section. It has a nominal yield stress of 1350 MPa and an ultimate nominal tensile strength of 1500 MPa [7]. Previous study on VHS members revealed that VHS tubes meet the ductility requirements specified in the current steel design standard [8]. VHS tubes also demonstrated higher buckling capacity in axial compression and in bending than cold-formed CHS with a nominal strength less than 450 MPa [9,10]. While high strength steels have many advantages over conventional steels, the property change in the welded connections of high strength steels due to heat affected zone (HAZ) softening seems inevitable [11]. There is a reduction in strength in the welded connections of VHS tubes. The strength of butt-welded connections was about 50% of the parent metal [12–14]. Another application of VHS tubes is through fabricated sections utilizing VHS tubes as corners [15,16], where longitudinal welding is used.

Zhao et al. [15] carried out a series of stub column tests on fabricated square and triangular sections utilizing VHS circular steel tubes. The VHS tubes were placed at each corner of the section and welded to Grade 350 steel plates as shown in Fig. 1(a). The load carrying capacity of the fabricated section was found to be 3 to 4 times the calculated nominal section capacity of a corresponding welded square or triangular box section without tubes. Mashiri et al. [16] conducted compressive tests on concrete filled stub columns fabricated using VHS tube and mild steel plates as shown in Fig. 1(b). Test results were compared with the predictions from different design codes. The heat affected zone softening in the longitudinally welded fabricated sections seemed not severely affected the performance of the structure. Nevertheless, a strength reduction of 50% has been used to predict the load carrying capacity of fabricated sections [15]. There is a lack of understanding of strength reduction in HAZ of VHS tubes in the case of longitudinal fillet welds. The strength reduction of 50% may be too conservative for the case of longitudinal fillet welding. This study aims to fill the knowledge gap of HAZ softening in longitudinal fillet welded VHS tubes.

To this end, VHS tubes were fillet welded to mild steel plates in the longitudinal direction using the Gas Tungsten Arc Welding (GTAW) method. Vickers hardness on the welded section was measured in order to identify the heat affected zone. Vickers hardness was also measured on a transverse fillet welded VHS tube section in order to compare the hardness results. Compressive tests were conducted on VHS short columns longitudinally welded with one or two mild steels plates. Results were compared with that of VHS tubes without welding. A strength reduction factor was introduced to calculate the capacity of the welded VHS tubes. The new strength reduction factor was applied to the prediction of load carrying capacity of the following sections: (i) VHS tubes longitudinally fillet welded to plates; (ii) square fabricated sections [15]; (iii) triangular fabricated sections [15]; (iv) concrete-filled square fabricated sections [16] and (v) concrete-filled triangular fabricated sections [16].

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http://dx.doi.org/10.1016/j.jcsr.2015.09.008

Nomenclature

A	Cross-sectional area of VHS tube
A_c	The area of the concrete
A_e	Plate effective cross-sectional area
A_{HAZ}	The area of the HAZ
B	Width of mild steel plate
e	Axial shortening
f_c'	The compressive strength of the concrete
f_{HAZ}	The ultimate strength in the HAZ of VHS tube
f_{VHS}	The measured ultimate strength of VHS tube
f_{weld}	Strength of welded VHS tube
$f_{\mathrm{y.plt}}$	The measured yield stress of steel plate
GTAW	Gas Tungsten Arc Welding
HAZ	Heat affected zone
HV	Vickers hardness
k_f	Form factor of VHS tube
LVDT	Linear Variable Differential Transformer
P_{m}	Theoretical compressive capacity of the welded VHS tube
$P_{\mathrm{m.plt}}$	The capacity of the steel plate
$P_{\mathrm{m.C}}$	The capacity of the concrete
$P_{\mathrm{m.VHS}}$	The axial compressive capacity of welded VHS tube
P_{ult}	The ultimate load in compressive test
P_{VHS}	The ultimate load of non-welded VHS tube
R_{P_ult}	The ratio of the ultimate load of welded VHS tube to that of non-welded VHS tube
n	The number of welded plates
s	Weld leg length
t	The wall thickness of VHS tube
T	The thickness of steel plate
VHS	Very high strength
ϕ	Strength reduction factor in the HAZ
λ_e	Plate yield slenderness
λ_{ey}	Plate yield slenderness limit

2. Specimen preparation

2.1. Material properties

Tensile coupon tests were conducted in [7,8] on VHS tubes to determine the material properties including the two sizes used in this study. The average tensile yield stress was about 1361 MPa and the average ultimate tensile strength was about 1513 MPa for the VHS tubes. The properties of the mild steel plate used in this study were determined through tensile coupon tests in accordance with the Australian Standard AS 1391 [17]. Two tensile coupon specimens were cut from a Grade 300 mild steel plate with a thickness of 3 mm. An average tensile yield stress of 310 MPa and an average ultimate tensile strength of 383 MPa were obtained for the steel plate. Fig. 2 shows the typical stress and strain curves of the VHS tube and steel plate. The weld metal used in the welding was AWS A5.18: ER70S-6 low carbon steel rod that had a tensile strength of 500 MPa according to the material data sheet.

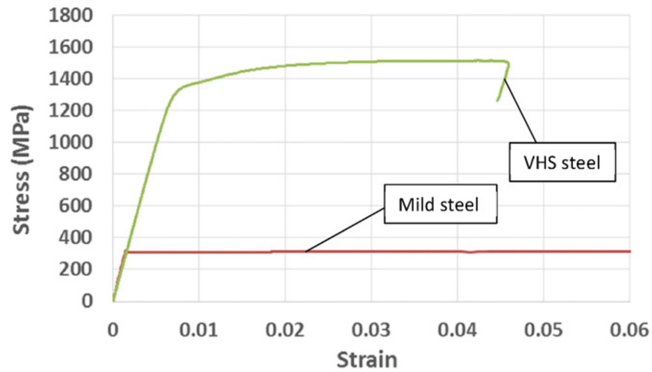

Fig. 2. Typical stress and strain curves of VHS tube [8] and mild steel plate.

2.2. Welding procedures

Each VHS tube was cut into 200 mm in length and welded to one or two steel plates longitudinally using the Gas Tungsten Arc Welding (GTAW) method. When two plates were welded, the angle between the two plates was 90° that was similar to a VHS tube in a fabricated square box section. The welding was carried in accordance with AS/NZS1554.4 [18]. A design throat thickness of 3 mm was determined by taking into account the minimum size of fillet welds specified in [19].

2.3. Specimen dimensions

The VHS tubes had a nominal diameter of 38 mm and thicknesses of 1.6 mm and 1.8 mm respectively while the steel plate had a thickness of 3 mm. A total of 18 specimens were welded as shown in Fig. 3. The geometric dimensions (D, t, and B) are defined in Fig. 4. The measured dimensions of all the specimens are given in Table 1. The first letter in a specimen label (C) refers to the compression test followed by a number that refers to the number of plates welded to the VHS tube. The symbols S1–S9 refer to the specimen number. Two samples were sectioned for hardness measurement with the other 16 samples for compressive testing.

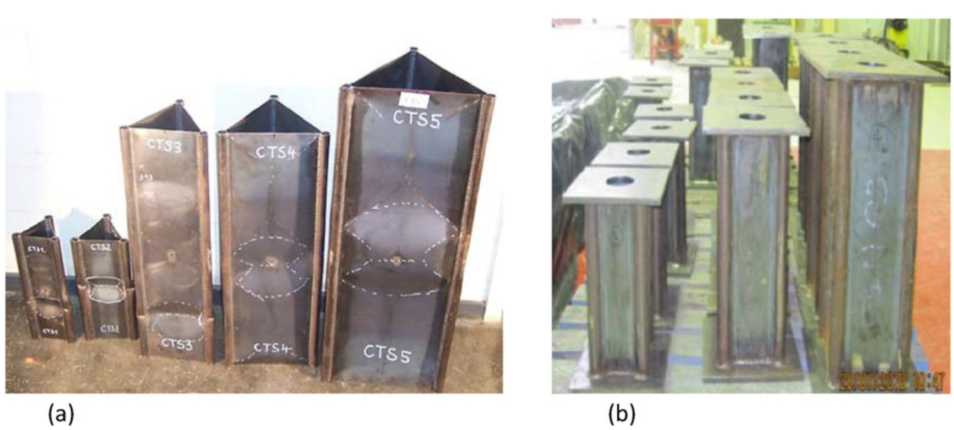

Fig. 1. (a) Fabricated square and triangular sections [15]. (b) Concrete filled stub columns fabricated using VHS tube and mild steel plates [16].