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COMPRESSION TESTS ON HIGH STRENGTH S690 WELDED SECTIONS WITH VARIOUS HEAT ENERGY INPUT

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Abstract. *Over the past twenty years, conflicting research findings have been reported on mechanical properties of high strength S690 welded sections due to different welding procedures and parameters adopted during welding. In order to quantify adverse effects on mechanical properties of these S690 steel welded sections, a total of 12 spliced S690 welded H-sections with different heat input energy adopted in the welding processes have been conducted to examine their deformation characteristics under compression, in particular, their cross section resistances. It is demonstrated that by a proper control on the heat input energy during welding, it is possible to control or even eliminate any reduction to the mechanical properties of these spliced S690 welded H-sections under compression.*

Keywords: *High strength steels; welding; welded H-sections; heat input energy*.

1. INTRODUCTION

High strength S690 steels are efficient steel constructional products which possess mechanical strengths two to three times to those of normal strength steels, such as S235 and S355 steels. Owing to their excellent strength-to-self weight ratios, they are highly desirable to be used in heavily loaded structures, leading to a potential saving in both materials and costs in the order of 30 to 50 %. Since 2000, high strength steels have been successfully used in key structural members of large lifting equipment, machinery and offshore structures. However, they have not been widely adopted in construction owing to potential adverse effects of welding on their microstructures which lead to significant reductions in their mechanical properties (Willms 2009). Hence, it is necessary to examine structural adequacy of these S690 welded sections with different heat input energy in order to ensure satisfactory structural performance of S690 welded members in construction.

1.1. Adverse effects of welding onto high strength steels

In general, welding in normal strength S355 steels does not cause any significant strength reduction as they are primarily ferritic or ferritic-pearlitic steels which microstructures do not undergo phase transformation during welding. However, high strength steels are primarily manufactured with heat treatments during steel-making, such as Quenching and Tempering for QT steels (Krauss 1980). These high strength steels possess highly favourable properties of strength, ductility and toughness. However, large heating/cooling cycles induced during a practical welding process will trigger phase transformation, recrystallization and grain growth in heat-affected-zones (HAZ) of their welded joints. QT steels possess different continuous cooling transformation (CCT) characteristics, and thus, various phases of the QT steels will be formed. Hence, significant adverse effects on mechanical properties of these welded joints at locations within the HAZ, in particular decreased hardening due to softening, will be resulted, if the heat input energy, q (kJ/mm), adopted during welding is not properly controlled (Easterling 1992).

1.2. Related investigations on high strength S690 steel plates and their welded sections

In order to promote effective use of the high strength S690 steels in construction, it is essential to examine mechanical properties and structural behaviour of the S690 steel members and their joints. A comprehensive research programme on experimental and numerical investigations was conducted by the authors on i) mechanical properties of the S690 steels and their welded sections under monotonic and cyclic actions (Liu et al. 2017, Liu et al. 2018), ii) cross-sectional resistances of S690 welded H-sections as stocky columns (Wang and Chung, 2017), iii) member resistances of S690 welded H-sections as slender columns (Ma et al. 2017a, Ma et al. 2017b, Ma et al. 2017c), and iv) cross-sectional and member resistances of S690 welded I-sections as restrained and unrestrained beams respectively (Wang et al. 2017).

However, it becomes obvious in many cases that reductions in various mechanical properties of these high strength S690 welded sections are found to be significantly less severe than anticipated. In general, there is a lack of systematic experimental evidence on such reduction on the mechanical properties of these S690 welded sections as well as on the structural behaviour of these S690 steel members.

In this paper, an experimental investigation is undertaken to examine structural behaviour of high strength S690 steel spliced welded H-sections under compression. It aims to quantify compressive behaviour of these welded sections manufactured with different heat input energy during welding, and hence, to establish whether there are significant reductions in the mechanical properties of these S690 welded sections.

2. EXPERIMENTAL TESTS

In order to assess any adverse effect of welding onto the mechanical properties of the S690 welded H-sections, a total of 12 compression tests on 4 different cross sections, namely, Sections C1 to C4 with butt welded joints at mid-height, i.e. S690 spliced welded H-sections, were carried out. Figure 1 illustrates these four welded H-sections with different cross-sectional dimensions, and steel plates with three different thicknesses, i.e. 6, 10 and 16 mm, are used in these sections. Table 1 presents their mechanical properties obtained in standard coupon tests.

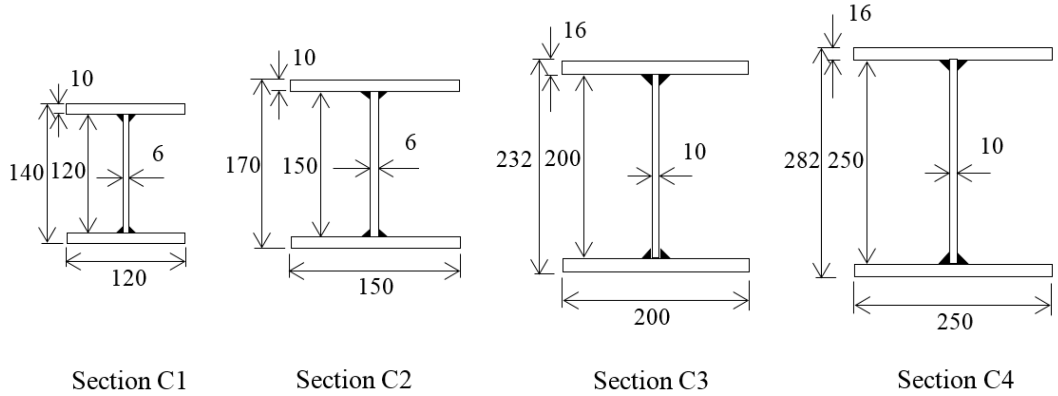

Figure 1. Nominal cross sectional dimensions of S690 welded H-sections

Table 1. Material properties of S690 steels and welding materials

Plate thickness (mm)	Yield strength f_y (N/mm^2)	Tensile strength f_u (N/mm^2)	Young's modulus E (kN/mm^2)	Strain at tensile strength ε_u (%)	Elongation at fracture ε_L (%)
6	722	847	209	6.36	18.8
10	784	874	206	7.42	19.8
16	745	832	216	6.62	19.6

2.1. Test programme and set-up

Table 3 summarizes the test programme of the compression tests, and a total of 12 sections with welded splices at mid-height of the sections are tested. It should be noted that in this test series, only three different values of the heat input energy q are adopted during welding of the butt welded joints, i.e. q = 1.0, 1.5 and 2.0 kJ/mm. Refer to Table 2 for various welding procedures and parameters adopted during butt welding of the steel plates of these sections. Two different testing systems are employed to conduct compression tests on various sections according to expected failure loads of these stocky columns. The testing systems are shown in Figure 2, i.e. Sections C1 and C2 are tested with a MTS Testing System with a loading capacity of 4,000 kN while Sections C3 and C4 are tested with a Hydraulic Servo Control Testing System with a loading capacity of 10,000 kN. Both ends of the H-sections are properly welded onto thick end plates to ensure consistent deformations of the sections under compression.

Table 2. Welding parameters for butt welds of S690 steels

Plate thickness (mm)	Welding parameters				
	Voltage U (V)	Current I (A)	Welding speed v (mm/s)	Heat input energy q (kJ/mm)	No. of pass
6	20	175	2.9	1.03	1
	24	220	3.0	1.50	1
	22	215	2.0	2.01	1
10	20	170	2.9	1.00	2
	24	220	3.0	1.50	2
	24	245	2.5	2.00	2
16	20	180	3.0	1.02	3
	21	235	2.8	1.50	3
	25	280	3.0	1.98	3

* By skilled welders with GMAW.

Table 3: Section resistances of S690 spliced welded H-sections under compression

Specimen	Heat input energy q (kJ/mm)	Section classification	Design resistance $N_{c,Rd}$ (kN)	Measured resistance $N_{c,Rt}$ (kN)	$N_{c,Rt}$ / $N_{c,Rd}$
C1S-1-bw	1.0	Class 1	2531	2707	1.07
C1S-2-bw	1.5		2508	2663	1.06
C1S-3-bw	2.0		2507	2660	1.06
C2S-1-bw	1.0	Class 3	3166	3232	1.02
C2S-2-bw	1.5		3117	3206	1.03
C2S-3-bw	2.0		3134	3240	1.03
C3S-1-bw	1.0	Class 2	6446	7047	1.09
C3S-2-bw	1.5		6351	7022	1.11
C3S-3-bw	2.0		6383	7027	1.10
C4S-1-bw	1.0	Class 3	8050	8453	1.05
C4S-2-bw	1.5		7955	8472	1.06
C4S-3-bw	2.0		8121	8548	1.05

a) MTS 400 tons Testing System

b) 1000 tons Hydraulic Servo Control Testing System

Figure 2. Overview of compression tests on S690 welded H-sections

2.2. Test results

All the tests have been conducted successfully. Typical deformed shapes of these spliced welded H-sections after tests are shown in Figure 3. It should be noted that, in all cases, symmetrical local buckling appears in both flanges of these spliced welded H-sections while complementary local buckling is also found in their web plates. Hence, the failure mode of these stocky columns is shown to be plastic local buckling in both the flange and the web plates of these H-sections.

Heat input energy, q (kJ/mm)		
1.0	1.5	2.0
 Section C3S-1-bw	 Section C3S-2-bw	 Section C3S-3-bw

Figure 3. Typical deformed shapes of S690 welded H-sections after tests

The measured applied load vs axial shortening curves of all these spliced sections are plotted onto the same graph in Figure 4 for easy comparison. It is evident that all these curves extend above the respective design section resistances $N_{c,Rd}$ of these Sections. All Sections C1S and C3S exhibit significant deformation ductility under compression, but there is little ductility in all Sections C2S and C4S. This agrees with the section classification obtained in accordance with the current classification rules for welded cross-sections given in EN 1993-1-1(CEN, 2005).

Table 3 presents the measured section resistances of all these S690 spliced welded H-sections, $N_{c,Rt}$, together with their design section resistances, $N_{c,Rd}$. The design resistances of the spliced welded H-sections are given by:

$$N_{c,Rd} = 2\,A_f \times f_{y,f} + A_w \times f_{y,w} \qquad (1)$$

where

$f_{y,f}$ and $f_{y,w}$ are the measured yield strengths of the flange and the web plates of the welded H-section respectively;

$$A_f = b \times t_f \qquad (2)$$

$$A_w = (h - 2t_f) \times t_w \qquad (3)$$

where

b and t_f are the measured width and the measured thickness of the flange plate respectively; and

h and t_w are the measured overall depth and the measured thickness of the web plate of the welded H-section respectively.

It is shown that all the measured section resistances, $N_{c,Rt}$, are larger than the design section resistances, $N_{c,Rd}$, and the ratios of $N_{c,Rt}$ to $N_{c,Rd}$ range from 1.02 to 1.11 with an average value of 1.06. Hence, there is no reduction in the section resistances of these spliced welded H-sections when the heat input energy q adopted during welding ranges from 1.0 to 2.0 kJ/mm. Consequently, Equation (1) is shown to be applicable to predict the section resistances of these stocky columns of S690 spliced welded H-sections under compression.

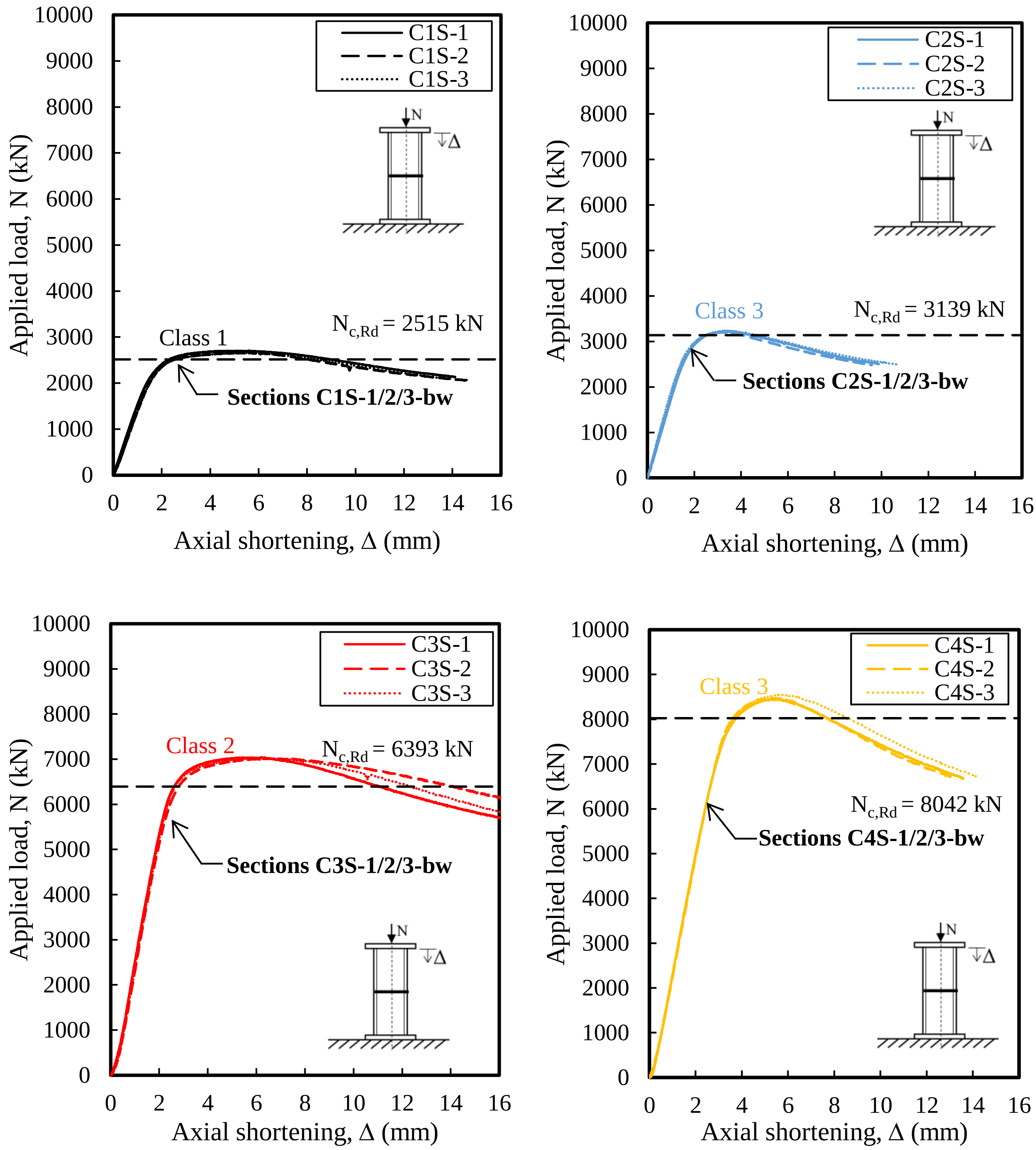

Figure 4. Measured applied load vs axial shortening curves of S690 welded H-sections

3. CONCLUSIONS

In order to assess any adverse effect of welding onto the mechanical properties of the S690 welded sections, a total of 12 compression tests on 4 different cross sections, namely, Sections C1 to C4, with butt welded joints at mid-height were carried out.

It should be noted that key test results, including the failure modes, the measured deformation characteristics, and the measured section resistances of all the 12 tests are presented in this paper. It is demonstrated that by a proper control on the heat input energy during welding, it is possible to eliminate any reduction to the mechanical properties of these S690 welded sections under compression. Consequently, experimental evidence on structural adequacy of these high strength S690 steel welded joints with different heat input energy adopted in the welding processes is provided scientifically to confirm applications of these high strength S690 steel in construction.

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