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Concentrically loaded slender square hollow and composite columns incorporating high strength properties

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ABSTRACT

This paper presents an experimental investigation of longitudinally slender box sections (HS) having compact and non-compact cross-sections as well as slender composite sections (CB) fabricated from high strength steel (HSS) and high strength concrete (HSC). Fifteen test specimens (HS) and thirty nine test specimens (CB) having width to thickness ratios (b/t) ranging from 15 to 40 and slenderness ratios ranging from 18 to 124 were tested to failure. Finite element modelling (FEM) of the test specimens (HS and CB) was verified with the experimental results for further analysis. The FEM was used to investigate the effects of residual stresses induced from lightly and heavily welded box sections on the member capacity of slender box sections. The column curves of various design specifications pertaining to slender welded box sections were reviewed by the experimental and FEM peak strengths for the purpose of selecting the most appropriate curves for non-compact box sections. Likewise, the column curves pertaining to the slender composite sections were reviewed by the experimental and FEM peak strengths for the purpose of selecting the most appropriate curves for high strength composite columns fabricated from HSS (690 MPa) and HSC (80–130 MPa).

1. Introduction

Slender welded box columns and welded box sections filled with concrete (composite columns) have been used in the past to support the floors of multi-storey buildings and decks of motorway and railway. With the advent of high strength materials for structural usage, the capacity of both hollow and composite sections have been enhanced considerably [1]. Among others, Thai et al. [2] undertook an extensive numerical investigation of short composite sections fabricated from high strength properties. However, a limited number of investigations have been undertaken to date on both slender welded box columns as well as composite columns fabricated from 690 MPa high strength steel (HSS) and high strength concrete (HSC).

Based on experimental and numerical studies undertaken by Ban et al. [3] and Wang et al. [4], the slender welded box sections fabricated with 460 MPa steel plates exhibit higher overall buckling strengths on a non-dimensional basis, when compared with box sections fabricated from mild strength steel (MSS). As a result, the authors recommended a higher design buckling curve (b) of Eurocode 3 [5] for slender welded box sections fabricated from HSS. Likewise, Rasmussen and Hancock [6] recommended a higher buckling curve corresponding to $\alpha_b = -0.5$ of AS4100 for slender welded box sections (only for compact sections) fabricated from 690 MPa steel plates. The reason for the higher buckling strength is that the effect of the induced residual stress and global imperfection is less pronounced on box sections fabricated from HSS [4,7,8] than that of MSS.

The research as highlighted above only focused on compact welded box sections, which negate the local buckling effect. Usami and Fukumoto [9] conducted an experimental investigation on compact and non-compact welded box sections fabricated from HSS (690 MPa). Therein, the author revealed that an economical solution for welded box sections with slenderness ratios greater than 54 is obtained when the cross section of the box columns is non-compact. This means that the interaction between the local and global buckling is required to take place for an optimum solution. Degée et al. [10] undertook an experimental and a numerical study on class-4 sections having steel grade S355, S460 and S690. Therein, the author recommended a higher buckling curve (a) of Eurocode 3, which is also equivalent to the curve corresponding to $\alpha_b = -0.5$ of AS4100.

Khan et al. [11] measured the residual stress distributions of compact and non-compact welded box sections fabricated from 690 MPa steel, including lightly and heavily welded box sections.

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The measurement revealed that compressive residual stresses are higher than previously reported measurements [7,8,12,13,9]. Therefore, the current research aims to investigate the effect of residual stress distributions induced from lightly and heavily welded sections on slender compact and non-compact welded box columns fabricated from 690 MPa steel plates. Furthermore, this research also aims to review the current steel design standards (such as Australian Steel Standard (AS4100) [14], Eurocode 3 [15] and American Institute of Steel Construction (AISC) [16]), based on current experimental data.

Based on the analysis of the database, approximatively 80% of the total research concerning composite columns has been focused on short and low slender composite columns [17]. Examples include Kilpatrick and Rangan [18] who conducted 41 tests on circular composite columns incorporating HSS (410 and 435 MPa) and HSC (58 and 96 MPa) to investigate the behaviour of high strength composite columns, when subjected to singular and double curvature bending. Similarly, Vrcelj and Uy [19] investigated four square slender hollow and composite columns fabricated from HSS (400–450 MPa) and HSC (52–79 MPa) by subjecting the specimens to concentric loading. The analysis revealed that the buckling curve corresponding to $\alpha_b = -0.5$ of AS4100 predicted member capacities conservatively. Furthermore, Vrcelj and Uy [20] investigated slender columns with non compact box sections numerically to propose a design method for predicting the local buckling strength. Note that the numerical analysis considered HSS (690 MPa) and HSC (100 MPa) while any experimental data pertaining to slender composite columns fabricated from 690 MPa HSS and 100 MPa HSC was not available at the time.

Considering welded composite box sections fabricated from 690 MPa steel plates, Mursi and Uy [21] presented test results of four eccentrically loaded 3020 mm length square box sections having b/t values of 22, 32, 42 and 52 filled with 20 MPa concrete. The analysis from the test results concluded that all buckling curves of Eurocode 4 predict the member capacities of compact sections conservatively and overestimate member capacities of non-compact sections. In addition, Mursi and Uy [22] carried out biaxial loading tests on five slender square composite columns having b/t values of 24, 34, 44 and 54. Peak loads from the test results were conservative against the buckling curve (a) of Eurocode 4, $\alpha_b = -0.5$ of AS4100 and AISC [23].

Upon reviewing the published literature as highlighted above and as has been the case with slender welded box sections fabricated from HSS (690 MPa), limited experiments have been undertaken on composite box sections fabricated from HSS (690 MPa) and HSC (>80 MPa). Furthermore, part 6 of the Australian Bridge design - steel and composite construction (AS5100.6) [24], Eurocode 4 [25], AISC and Canadian Standard Association (CSA S16-09) [26] restrict the use of HSS (690 MPa) and HSC. Therefore, one of the main purposes of this current research is to review the current design buckling curves of the specifications for square composite columns fabricated from HSS (690 MPa) and HSC.

This paper presents an experimental and a numerical investigation of slender welded box sections (HS) and composite sections (CB), including compact and non-compact cross-sections. Nonlinear finite element models (FEMs) were developed and verified with the experimental results herein. This paper investigates the effects of induced residual stress on the member capacity of heavily and lightly slender welded box sections. Furthermore, the column curves of design specifications were examined by the experimental and FEM results for predicting slender welded box columns with compact and non-compact cross-sections as well as slender welded box composite sections. In addition, the member capacity of the composite sections having HSC (80–130 MPa) were investigated by using FEM for the purpose of selecting an appropriate column curve for AS5100.6.

2. Experimental investigation

2.1. Overview of test specimens

The experimental programme comprised a total of fifty five test specimens having width to thickness ratios (b/t) of 15, 20, 25, 30 and 40 and lengths (L) of 1060 mm, 2060 mm and 3060 mm, as listed in Tables 1,2. The experimental programme was categorised into two test series: box or hollow sections (HS) in Table 1 and composite sections (CB) in Table 2. Each test specimen is identified by its unique code name, as shown in Tables 1 and 2. For example, a test specimen, HS15SL1, from Table 1 can be explained as follows: HS refers to a hollow section; 15 refers to the b/t ratio; and SL1 refers to 1050 mm length slender column.

Plates of 5 mm thickness (690 MPa HSS) and single pass fillet welds were used to fabricate all test specimens (see Khan et al. [11] for information on weld material). Additionally, the stiffeners were fabricated at each end of the test specimens to avoid localised bearing failure during the experiment, as shown in Fig. 1. Standard coupon tests were undertaken to determine HSS properties: yield strain (ε_y), yield stress (σ_y), ultimate strength (σ_u) and modulus of elasticity (E), as summarised in Table 3. Based on the 0.2% proof stress, the tensile coupon tests provided an average σ_y of 762 MPa. Commercially available HSC (100 MPa) was used to fill up the hollow specimens to prepare for the test specimens (CB). Herein, HSC

Table 1
Dimensions of test specimens (HS).

Test specimens	b (mm)	t (mm)	b/t	L (mm)	L_e (mm)
HS15SL1	74.07	4.92	15	1060	1512
HS20SL1	99.39	4.92	20	1060	1512
HS25SL1	125.21	4.92	25	1060	1512
HS30SL1	149.92	4.93	30	1060	1512
HS40SL1	199.40	4.94	40	1060	1512
HS15SL2	74.57	4.93	15	2060	2512
HS20SL2	99.39	4.92	20	2060	2512
HS25SL2	124.70	4.94	25	2060	2512
HS30SL2	149.95	4.92	30	2060	2512
HS40SL2	199.64	4.93	40	2060	2512
HS15SL3	74.21	4.88	15	3060	3512
HS20SL3	99.44	4.92	20	3060	3512
HS25SL3	125.20	4.92	25	3060	3512
HS30SL3	150.32	4.92	30	3060	3512
HS40SL3	199.55	4.91	40	3060	3512