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An experimental assessment of hot-rolled carbon and stainless steel equal legs angles under compression

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Abstract

Although stainless steel mechanical properties are similar to their carbon steel counterparts, the nonlinear stainless steel characteristics naturally leads to diverse design recommendations. These peculiar features directly modifies the behaviour of the ultimate limit states related to instability. The Eurocode 3: Part 1-4 (2006) stainless steel design standard can be utilised for hot-rolled, welded and cold-formed cross-sections, but this standard prescriptions are very conservative due to the lack of tests. An instability limit state that presses for additional research is associated to hot-rolled stainless steel angles. This paper is centred in experiments made on hot-rolled carbon and stainless columns steel equal legs angles under compression. These experiments were carried out on 500 mm to 1000 mm columns lengths with failures involving flexural-torsional buckling.

Keywords

Stainless steel, tubular joints, numerical models, finite element analysis

1 Introduction

The utilisation of stainless steel profiles has been boosted in structures due to its numerous structural benefits and aesthetic features. Although stainless steel mechanical properties are similar to their carbon steel counterparts, the nonlinear stainless steel characteristics naturally lead to diverse design recommendations. These peculiar features directly modify the behaviour of the ultimate limit states related to instability. The Eurocode 3: Part 1-4 [1], stainless steel design standard can be utilised for hot-rolled, welded and cold-formed cross-sections, but this standard prescriptions are very conservative due to the lack of tests. An instability limit state that presses for additional research is associated with hot-rolled stainless steel angles. This paper is centred on experiments performed on hot-rolled carbon and stainless columns steel equal legs angles under compression. These experiments were carried out on 500 mm and 1000 mm columns lengths with failures involving flexural-torsional buckling.

2 Structural Design of Angles in Compression

Reynolds [2], conducted tests on 33 welded duplex stainless steel angles sections with three types of cross-sections. The tested angles had free and fixed rotations supports on the minor and major inertia axis, respectively. The experimental results were in good agreement with a flexural buckling curve evaluated with the tangent elasticity modulus. In this test programme, the flexural-torsional buckling limit state could not be assessed since the experimental was limited.

Gardner [3] and Afshan & Gardner [4], developed and improved the Continuous Strength Method (CSM) that considers the nonlinearity of the stainless steel tension versus strain curve, the strain capacity, and the strain hardening strength increase present in austenitic stainless steels.

Menezes [5] performed 13 tests in L64x64x6.35 austenitic hot-rolled angles with lengths varying between 250 mm to 1500 mm where the failure mode for lengths less than or equal to 750 mm was related to flexural-torsional buckling while for the other specimens was associated to flexural buckling. These test also confirmed that for normalised slenderness values less than 0.65, the Eurocode 3 Part 1-4 [1] is conservative while for slenderness above this limit, they lead unsafe design predictions. On the other hand, the Continuous Strength Method (CSM) proved to be unsafe for all tested stainless steel rolled sections.

The majority of investigations related to stainless steel sections compression response is still centred on cold-formed profiles where the results often consider the strain hardening and the interaction between local and global buckling modes. Limited studies include cases of flexural-torsional buckling in stainless sections, as reported in Afshan et al. [6], and Becque & Rasmussen [7].

Recently, Liang et al. (2019) [8], studied the flexural-torsional buckling response of fixed-ended hot-rolled austenitic stainless steel equal-leg angle section columns experimentally and numerically. These results were used to assess the precision of the most adopted design standards. The authors also concluded that a substantial amount of the design predictions led to unsafe designs, urging for the need for further design improvements.

3 Eurocode 3 design formulations

The European design codes, EN 1993-1-4 [1] and EN 1993-1-1 [10], utilise buckling curves for the design of stainless steel open section columns under flexural-torsional buckling. For hot-rolled equal-leg angle sections in compression, both design standards evaluate the flexural-torsional buckling resistance with Equation **Error! Reference source not found.**

$$N_{u,EC3} = \chi_{ft} A \sigma_{0.2} \quad (1)$$

where: $\sigma_{0.2}$ is the cross-section yield strength for carbon steel and proof stress at 0.2% for stainless steel, A is the cross-section area, i.e., A_g gross cross-section area for non-slender sections and A_{eff} effective cross-section area for slender sections while χ_{FT} is the flexural-torsional buckling reduction factor defined by Equation (2).

$$\chi_{FT} = \frac{1}{\phi + \left[\phi - \lambda_{ft}^2\right]^{0,5}} \leq 1 \quad (2)$$

The buckling coefficient ϕ is evaluated with Equation (3) where λ_{FT} is the flexural-torsional buckling slenderness calculated with Equation (4).

$$\phi = 0.5\left[1 + \alpha\left(\lambda_{ft} - \overline{\lambda}_0\right) + \lambda_{ft}^2\right] \quad (3)$$

$$\lambda_{FT} = \sqrt{\frac{A\sigma_{0.2}}{A_g N_{cr,ft}}} \quad (4)$$

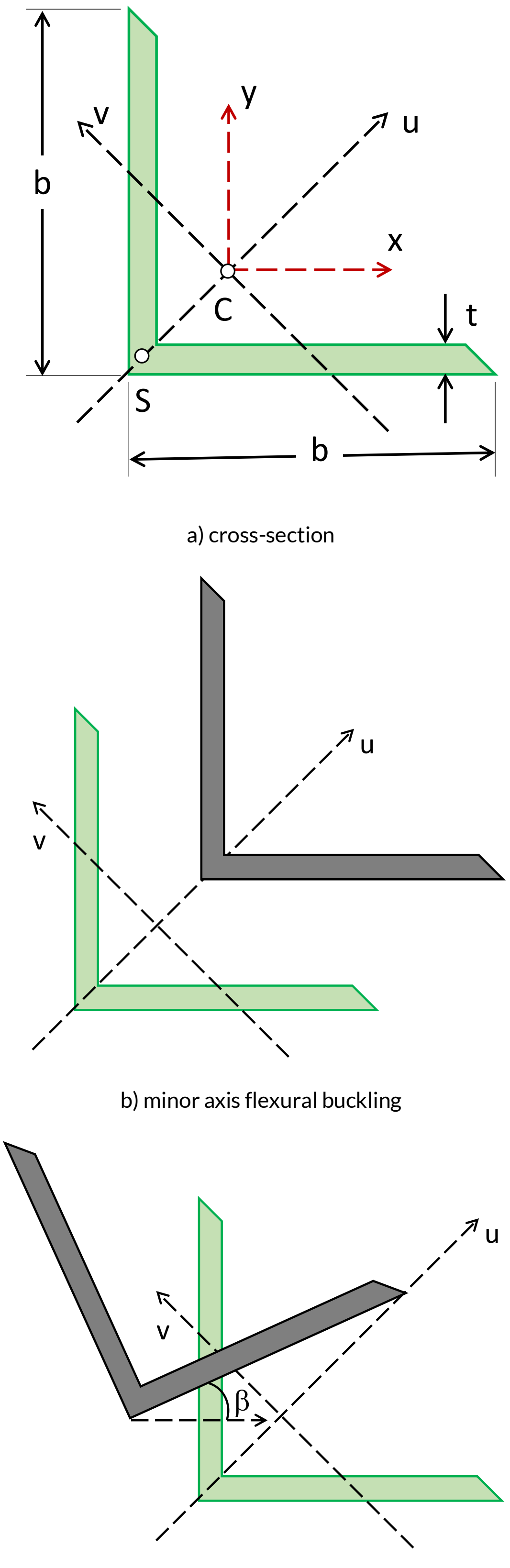
where α is the generalised imperfection factor, equal to 0.34, for stainless and carbon steel columns under flexural-torsional buckling, $\overline{\lambda}_0$ = 0.2 (for stainless and carbon steel) is the limiting normalised slenderness and $N_{cr,FT}$ is elastic critical flexural-torsional buckling load evaluated with Equation (5) in which $f_{cr,FT}$ is the elastic critical flexural-torsional buckling stress.

$$N_{cr,FT} = A_g f_{crFT} \quad (5)$$

The only difference between the European design codes EN 1993-1-4 [1] and EN 1993-1-1 [10] is related to the γ_{m1} partial coefficient factor that alters the design resistance to compression being equal to 1.0 and 1.1 for carbon and stainless steels, respectively. Since the present investigation directly compares the results of experiments in both cases, a factor equal to 1.0 will be utilised.

4 Experimental programme

The present investigation is centred on an experimental programme made on hot-rolled carbon and stainless columns steel equal legs angles under compression, whose design is controlled minor axis flexural and flexural-torsional buckling collapse modes as depicted in Figure 1. The investigated carbon and stainless cross-sections geometries are depicted in Table 1, where a small variation could be observed for the tested angle L64x64x4.8. The carbon and stainless tests varied between 150 mm up to 15000 mm but the present paper will be focused on two characteristic lengths, i.e. 500 mm and 1000 mm. More details about these tests can be found in Sirqueira [9].



c) flexural torsional buckling

Figure 1 Investigated angles sections & associated compression failure modes.

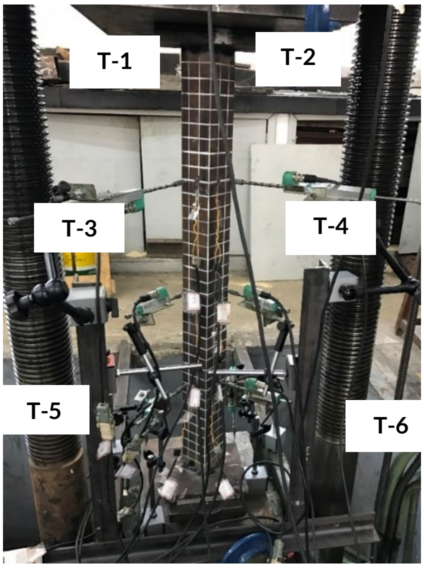
The physical properties such as Young's Modulus (E), yield stress for carbon steel and proof stress at 0.2% ($\sigma_{0.2}$) for stainless steel and ultimate stress (σ_u) were obtained from the coupon tension tests as can be observed in Table 2. Typical stress versus strain curves associated with these results are illustrated in Figure 2.

Table 1 Tested angles measured geometry – L64x64x4.8 (LC – Carbon & LS - stainless)

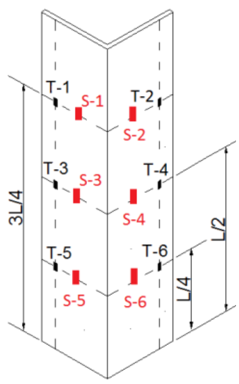
Test ID	b/t	L	b	t	b	t
LC_502	13.33	502	63.5	5.1	63.7	5.0
LC_503		503	63.2	4.9	63.5	5.0
LC_1002		1002	63.5	4.9	63.7	4.9
LC_1005		1005	63.5	5.0	63.6	4.9
LS_500_A		500	64.52	5.01	64.12	4.93
LS_500_B		500	64.42	4.78	64.00	4.73
LS_1000_A		1000	64.37	4.95	64.20	4.69
LS_1000_B		1000	64.61	4.85	64.18	4.86

Table 2 Experimental versus Eurocode 3 - 1.4 [1] comparison – L64x64x4.8

Test ID	E (GPa)	σ_y or $\sigma_{0.2}$ (MPa)	σ_u (MPa)
Carbon steel	203.2	338.3	476.4
Austenitic stainless steel	200.0	436.9	714.9

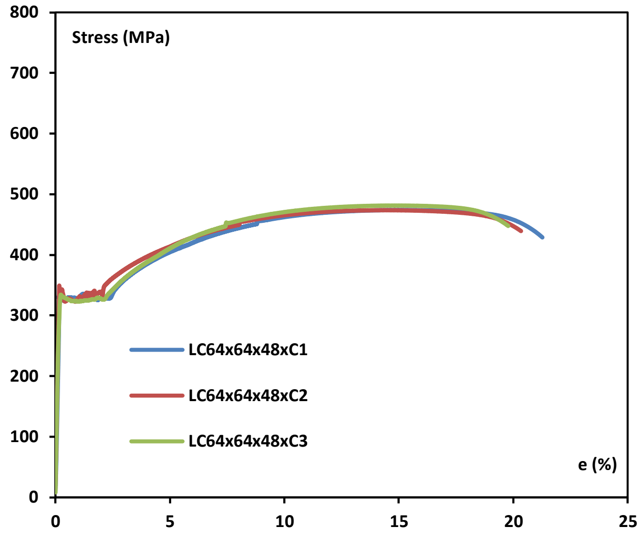


a) displacement transducers

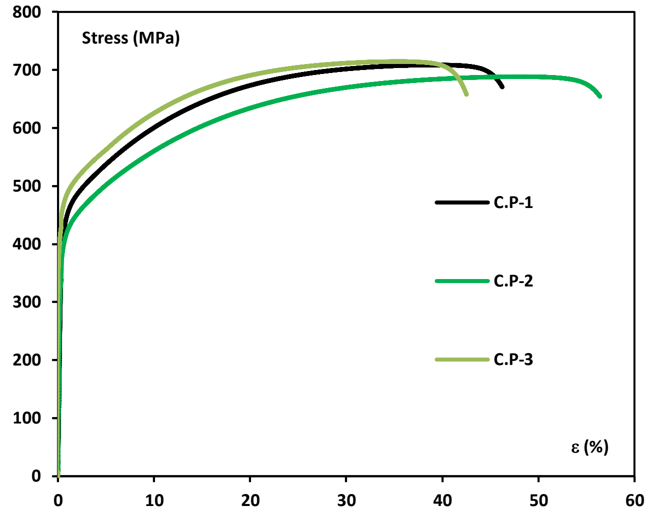


b) strain gauges

Figure 2 Test layout and instrumentation



a) carbon steel tensile coupon tests



b) austenitic stainless steel tensile coupon tests

Figure 3 Tensile coupon tests

The experiments were performed on a 3000kN controlled Universal Lousenhausen test system as can be visualised in Figure 3. The profiles were fabricated with cuts precisely perpendicular to the cross-sections while the base plate was welded, making sure its squareness and the verticality of the columns. Finally, the base plate and test system plate centroids were also forced to coincide, Figure 3.

During the setup phase, the specimens were under a 20kN preload followed by a load cycle with amplitude of 70kN and rate of 5kN/s. The test continued up to failure under displacement control at a 0.003 mm/s rate approximately. The test system top and bottom plates were fully fixed. These support conditions fully inhibit the rotation, only enabling a vertical displacement. The buckling length coefficient as expected is equal to 0.5.

The test instrumentation monitored key displacement and strains with LVDTs and linear strain gauges. The columns adopted LVDTs and strain gauges location is illustrated in Figure 3.

5 Experimental results

Figures 4 and 5 present the load versus axial displacement curves for 500 mm and 1000 mm length tested columns. A significant difference in terms of structural response was observed, for both investigated heights, when the carbon and stainless columns are compared.

Table 3 contains the test results in terms of ultimate loads as well as the European design codes EN 1993-1-4 [1] and EN 1993-1-1 [10] predicted design values. All the design predictions underestimated the column's load carrying capacities in values ranging from 52% up to 66% confirming the natural codes conservatism due to the lack of experimental evidence.

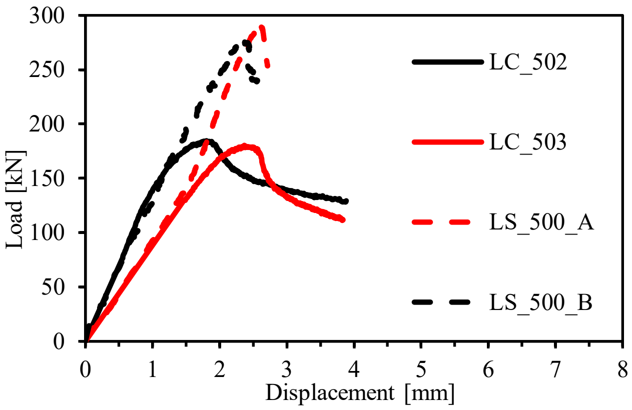


Figure 4 load versus axial displacement versus curves for the 500 mm columns

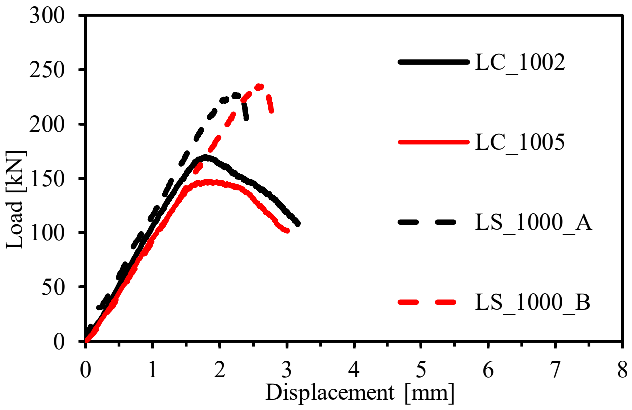


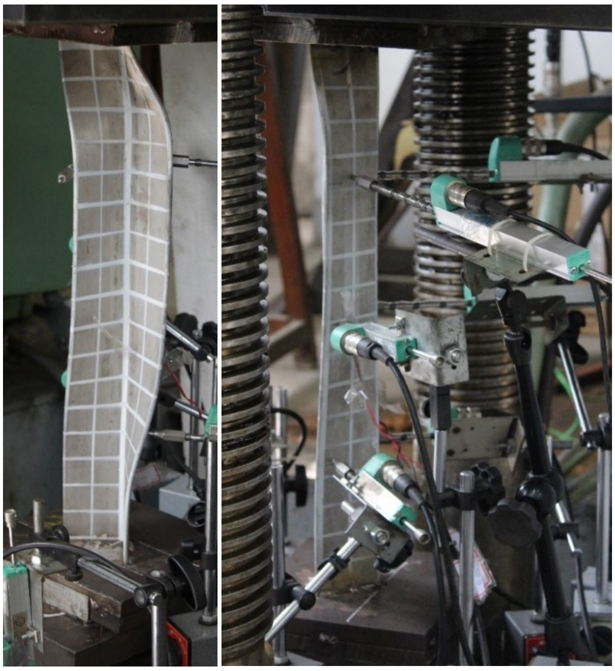
Figure 5 load versus axial displacement versus curves for the 1000 mm columns

Table 3 Experimental x Eurocode 3, 1.4 strength comparison– L64x64x4.8

Test ID	$N_{u,exp}$ [kN]	$N_{u,EC3}$ [kN]	$\frac{N_{u,exp}}{N_{u,EC3}}$
LC_502	184.54	138.48	1.66
LC_503	180.38	138.45	1.58
LC_1002	169.85	133.06	1.52
LC_1005	147.45	133.05	1.57
LS_500_A	253.92	157.09	1.62
LS_500_B	259.52	157.09	1.65
LS_1000_A	227.31	149.48	1.52
LS_1000_B	235.11	149.48	1.57

Figures 6 depicts the typical flexural-torsional buckling failure mode that occurred for both investigated lengths for the carbon and stainless steel columns.

a) LC_64x64x4,8_L500_2



b) LS_64x64x4,8_L500_2

Figure 6 Column deformed shapes

6 Conclusions

This paper presented test carried out to investigate the flexural torsional buckling behaviour of hot-rolled equal leg angle section columns made of ASTM A36 carbon and 304 austenitic stainless steel with 500mm and 1000 mm lengths. The test programme performed it possible to observe the structural response of columns made of angles with different normalised slenderness. The mechanical properties such as: Young's Modulus (E), yield stress (σ_y) for carbon steel and proof stress at 0.2% ($\sigma_{0.2}$) and ultimate stress (σ_u) were obtained from the tension coupon tests. The material characterisation confirmed the differences that exist between the carbons and stainless steel materials in terms of 0.2% ($\sigma_{0.2}$) and ultimate stress (σ_u) as well as their general linear (carbon) and non-linear (stainless) responses.

A 30% difference in terms of ultimate load and the structural response was observed, for both investigated heights, when the carbon and stainless columns were compared. The failure mode was associated with flexural-torsional buckling for all tested columns.

These results were finally used to evaluate the accuracy of the design methods present in the EN 1993-1-4 [1] and EN 1993-1-1 [10]. All the design predictions underestimated the column's load carrying capacities in values ranging up to 66%, confirming the natural codes conservatism due to the lack of experimental evidence.

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