

## **BEHAVIOUR OF AXIALLY LOADED CONCRETE - FILLED STAINLESS STEEL ELLIPTICAL STUB COLUMNS**

D. Lam<sup>1</sup>, L. Gardner<sup>2</sup> and M. Burdett<sup>1</sup>

<sup>1</sup>School of Civil Engineering, University of Leeds, Leeds, LS2 9JT, UK

<sup>2</sup>Department of Civil and Environmental Engineering, Imperial College, London, SW7 2AZ, UK

### **ABSTRACT**

This paper presents the details of an experimental investigation on the behaviour of axially loaded concrete-filled stainless steel elliptical hollow sections. The experimental investigation was conducted using normal and high strength concrete of 30 and 100 MPa. The current study is based on stub column tests and is therefore limited to cross-section capacity. Based on the equations proposed by the authors on concrete-filled stainless steel circular columns, a new set of equations for the stainless steel concrete-filled elliptical hollow sections were proposed. From the limited data currently available, the equation provides an accurate and consistent prediction of the axial capacity of the composite concrete-filled stainless steel elliptical hollow sections.

### **KEYWORDS**

Composite column, Concrete-filled, Elliptical hollow sections, Eurocodes, Experiments, High strength concrete, Stainless steel, Tubular construction

### **INTRODUCTION**

Composite sections are becoming increasingly popular in construction. Harnessing the strengths of two different materials to form a composite section can be beneficial in terms of both structural performance and cost. An example of a widely used composite section in construction is composite slabs; this form of construction has become very popular in recent years, where steel beams and concrete slabs act compositely to resist load. There has also been a recent surge in the popularity of composite columns. In composite columns, steel and concrete are combined such that the beneficial qualities of both materials can be used, making the column perform better structurally than a steel column, or a reinforced concrete column. It is also important that these improvements can be achieved without significant increases in cost. In addition to the improvements of the basic structural qualities of the section, concrete-filled columns also perform well under seismic loading and elevated temperatures.

The elliptical hollow section is also becoming increasingly popular in construction. The aesthetic appeal makes the section popular with both architects and engineers. The elliptical section has one significant advantage over circular and square sections; the presence of both a minor and major axis. Since the majority of steel framed buildings consist of one way spanning floor systems, columns are often arranged to withstand a large load and moment in the major axis, and a smaller load and moment in the minor axis. This allows designers to arrange their structures accordingly giving excellent scope for economic design. Under pure axial compression, circular concrete-filled tubes are generally stronger than elliptical sections. However, if a circular column also has to resist a moment about one axis, design can become uneconomical. The unnecessarily large inertia in the weak axis means that material and floor space is wasted. In this circumstance, the ellipse has a significant advantage over the circular sections.

In the present study, the behaviour of concrete-filled composite stainless steel elliptical hollow sections was investigated. In addition to the section shape and steel material properties, the influence of the concrete strength to the composite columns is also examined. The use of high strength concrete can result in smaller cross-sectional areas and in turn greater floor space, which can be very important in city centre buildings where the cost of floor space is at the premium.

Research into the behaviour of concrete-filled steel tubes dates back to the 1960s, but many of the significant developments have come in recent years. Most of the research has been carried out on circular, square or rectangular tubes made from carbon steel. There is currently no information on concrete-filled stainless steel elliptical hollow sections.

Gardner and Jacobson (1967) tested 22 composite columns under axial compression with  $D/t$  ratios varying between 30 and 40. The delay of local buckling in the steel tube and subsequent higher compressive strains that could be achieved were attributed to the stabilising effect of the concrete core. O'Shea and Bridge (1996, 2000) tested a number of concrete-filled circular thin-walled steel tubes with  $D/t$  values greater than 55 but lower than 200 and showed that the degree of concrete confinement offered by a thin-walled circular steel tube to the concrete core is dependent on the means of loading introduction. The greatest confinement occurs for thin-walled steel tubes where only the concrete core is loaded, and the steel tube acts as a circumferential restraint, without contributing to the axial capacity. Schneider (1998) carried out axial compression tests to determine the effects of tube thickness and tube shape on ultimate strength. Work by Uy (1998) also showed that higher  $b/t$  ratios lead to lower failure loads.

Research on elliptical shaped tubes is limited to date. However, Chan and Gardner (2008) have examined the compressive resistance of carbon steel elliptical hollow sections experimentally. The effect of confinement in elliptical shaped columns has also been investigated by Tan and Yip (1994). It was found that concrete columns that were reinforced with elliptical hoops exhibited effective lateral confinement, which resulted in an increase in strength and ductility of the concrete. Teng and Lam (2002) used a fibre-reinforced polymer jacket to provide lateral confinement to an elliptical concrete column. This is known to be a very effective technique for circular columns, but less effective for square or rectangular columns. Lam and Testo (2007) carried out tests on concrete-filled carbon steel elliptical sections. A total of 12 specimens were tested with wall thickness values of 4 mm, 5 mm, 6.3 mm and concrete core strength of 30 MPa. Results showed that for composite columns of 4 mm wall thickness, peak load was achieved at low deflection whilst for sections with wall thickness of 6.3 mm, ultimate load was achieved and maintained following large deformation values. The confinement effects were particularly evident in the 'core only' loaded tests where higher confinement was clearly provided by the thicker steel sections. Further analysis is reported by Yang *et al* (2008).

Studies into the structural performance of stainless steel tubular members have been reported by Rasmussen and Hancock (1993a, b) and Gardner and Nethercot (2004a, b), who investigated the compressive and flexural response of stainless steel hollow sections. The structural behaviour of high strength stainless steel tubular members has been studied by Young and Lui (2005), Ellobody and Young (2005) and Gardner *et al.* (2006). Research into the structural behaviour and design of concrete-filled stainless steel tubes has been rather limited, with the only reported studies to date by Young and Ellobody (2006), Ellobody and Young (2006) and Lam and Gardner (2008). These results are contributed to the present study of the concrete-filled stainless steel elliptical hollow sections.

## EXPERIMENTAL STUDY

An experimental study was performed to assess the compressive behaviour of concrete-filled stainless steel elliptical sections. Three cross-sections of elliptical hollow section (EHS) were investigated – EHS 121×76×2, EHS 121×76×3 and EHS 86×58×3. For each section size, three stub column tests were performed – one on the empty stainless steel tube and two concrete-filled specimens with normal strength (30 MPa) and high strength (100 MPa) concrete. Tests were also conducted on the constituent materials – tensile tests on coupons extracted from the stainless steel tubes and cube and cylinder tests on the concrete. The geometric properties for all the specimens are listed in Table 1.

Table 1: Measured geometric properties of the specimens

Specimens	Length, $L$ (mm)	Larger outer diameter, $2a$ (mm)	Smaller outer diameter, $2b$ (mm)	Thickness, $t$ (mm)	Steel area, $A_s$ (mm <sup>2</sup> )	Concrete area, $A_c$ (mm <sup>2</sup> )
EHS 121×76×2	242	123.7	76.9	1.84	569.0	-
EHS 121×76×2 – C30	243	123.9	77.0	1.88	581.9	6907
EHS 121×76×2 – C100	244	124.0	76.4	1.88	580.4	6856
EHS 121×76×3	242	121.5	77.1	3.00	889.9	-
EHS 121×76×3 – C30	242	121.0	78.4	2.98	905.0	6542
EHS 121×76×3 – C100	242	121.3	78.0	3.00	910.4	6517
EHS 86×58×3	172	85.6	57.2	3.11	667.1	-
EHS 86×58×3 – C30	174	85.4	57.3	3.20	677.2	3144
EHS 86×58×3 – C100	176	85.5	57.0	3.17	685.3	3161

### Concrete Properties

Two nominal concrete strengths – C30 and C100 were studied. The concrete was produced using commercially available materials with normal mixing and curing techniques; the mix designs are shown in Table 2 together with the cube and cylinder strengths at the test day. At the time of each series of stub column tests, two standard cube tests and two standard cylinder tests were performed. The strength development of the concrete was monitored over a duration of 28 days by conducting periodic cube and cylinder tests – the development of cube strength is illustrated in Figure 1.

Table 2: Concrete mix proportions (% by weight) and the compressive strength (test days)

Grade	Cement	Fines	Coarse	w/c ratio	Silica fume	Super-plasticiser	$f_{cu}$ (N/mm <sup>2</sup> )	$f_{ck}$ (N/mm <sup>2</sup> )
C30	1.0	2.5	3.5	0.65	0	0	46.3	37.0
C100	1.0	1.5	2.5	0.30	0.1	0.03	109.4	90.0

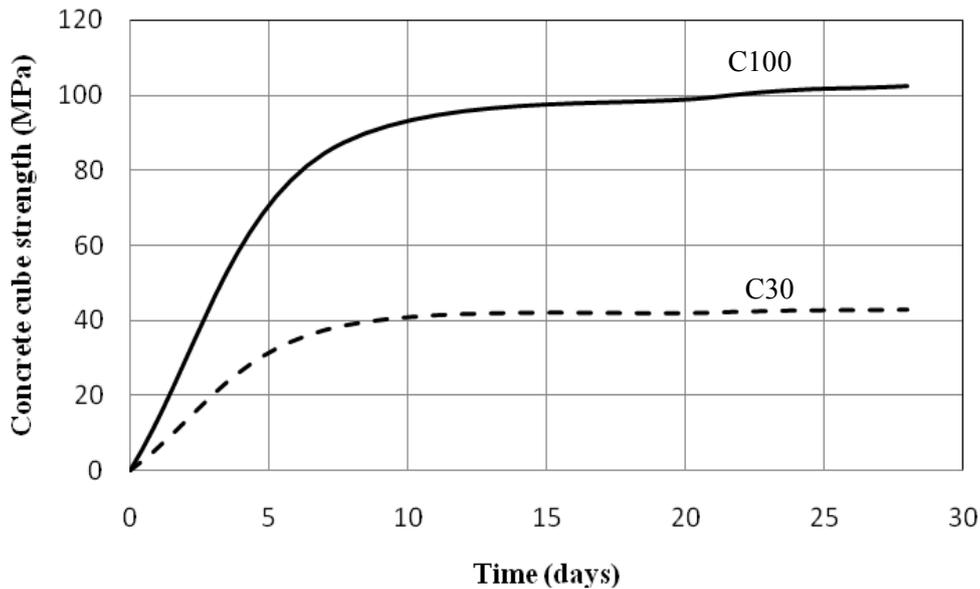


Figure 1: Concrete strength development

### ***Stainless Steel Properties***

Tensile coupons were machined from the stainless steel sections and tested to determine the basic material stress-strain characteristics. For the coupons cut from the EHS, some flattening of the ends of the samples occurred during gripping but this was remote from the necked region and believed not to influence the resulting stress-strain characteristics. The tests were carried out in accordance with EN 10002-1. The measured tensile stress-strain curves are shown in Figure 2. The key material parameters have been summarised in Table 3, where  $E$  is the initial tangent (Young's) modulus,  $\sigma_{0.2}$  and  $\sigma_{1.0}$  are the 0.2% and 1.0% proof strengths respectively,  $\sigma_u$  is the ultimate tensile strength and  $n$  and  $n'_{0.2,1.0}$  are strain hardening exponents for the compound Ramberg-Osgood material model described in Gardner and Ashraf (2006). This adopted compound Ramberg-Osgood model was developed on the basis of a two-stage version of the original expression by Ramberg and Osgood (1943).

Table 3: Measured stainless steel material properties

Specimen	$E$ (N/mm <sup>2</sup> )	$\sigma_{0.2}$ (N/mm <sup>2</sup> )	$\sigma_{1.0}$ (N/mm <sup>2</sup> )	$\sigma_u$ (N/mm <sup>2</sup> )	$n$	$n'_{0.2,1.0}$
EHS 121×76×2	193900	380	426	676	7.8	2.9
EHS 121×76×3	194100	420	460	578	9.7	4.0
EHS 86×58×3	194500	339	368	586	14.0	1.8

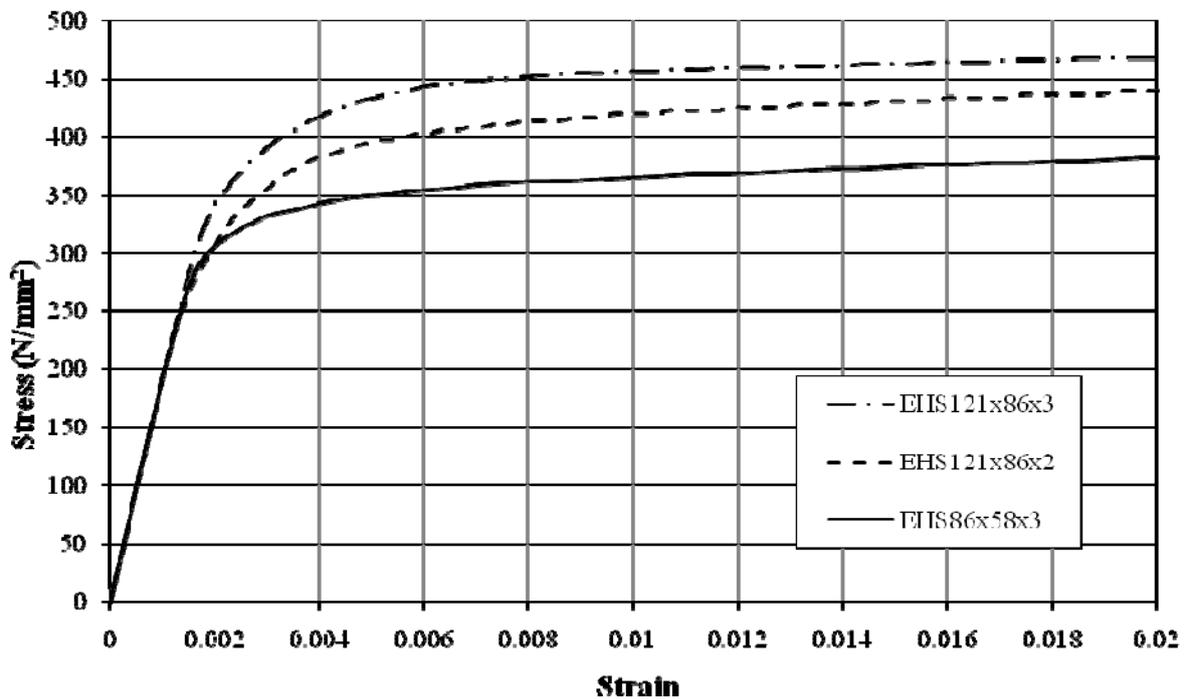


Figure 2: Tensile stress-strain curves of material from stainless steel sections

### *Composite column tests*

Testing of the composite columns was carried out using a 3000 kN capacity ToniPACT testing machine and the experimental set up is shown in Figure 3. Both ends of the specimens were milled flat and capped. Rigid steel end plates were employed in order to distribute the applied load uniformly over both the concrete and steel section for the composite loaded columns. Each specimens was loaded at 50 kN intervals at the beginning of the test (i.e. in the elastic region) and at 10 kN intervals after the column began to yield, in order to have sufficient data points to capture the ‘knee’ of the load-deflection curve. A linear variable differential transducer (LVDT) was used to monitor the vertical deformation. Loading rates were manually controlled and all the readings were recorded once both load and strain had stabilized. Beyond the initial drop of load, testing was continued until excessive deformation of the column was observed. After the tests, the specimens were removed, photographed and carefully examined.



Figure 3: Test set-up for EHS composite column

For the unfilled EHS columns, the typical mode of failure was inward local buckling, as shown in Figure 4, while for the concrete filled columns, failure was by outward local buckling and concrete crushing, as shown in Figure 5. The buckling of the composite stainless steel concrete-filled EHS stub column is mainly caused by the expansion of the concrete under axial load. The steel column provided confinement for the concrete as it expands and helped maintaining its strength and ductility.

Figures 6 – 8 show the axial load vs. displacement curves for all the EHS columns. The results showed the clear advantage of composite stainless steel columns over the bare steel counterpart. It can be observed from the stub column tests that the specimens with the smaller  $D/t$  ratio stainless steel EHS behaved in a more ductile manner which would suggested better confinement is provided by the steel sections. In addition, composite columns with C30 concrete infill behaved much more ductile at failure in compare with the composite columns filled with C100 concrete.



Figure 4: Mode of failure of the unfilled EHS columns



Figure 5: Comparison between tested and untested composite EHS column

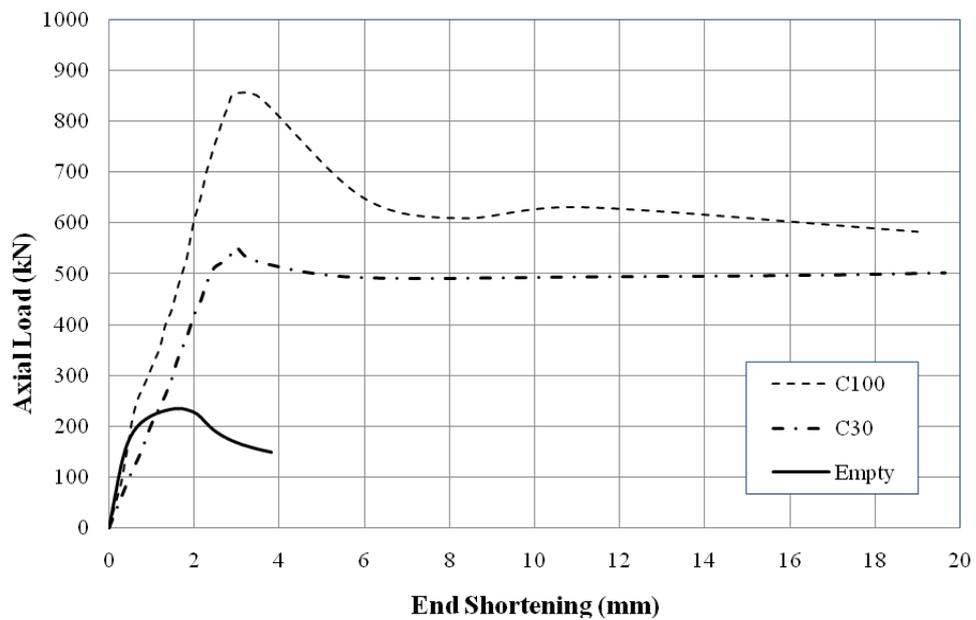


Figure 6: Axial load versus end shortening curves for EHS 121×76×2 composite columns

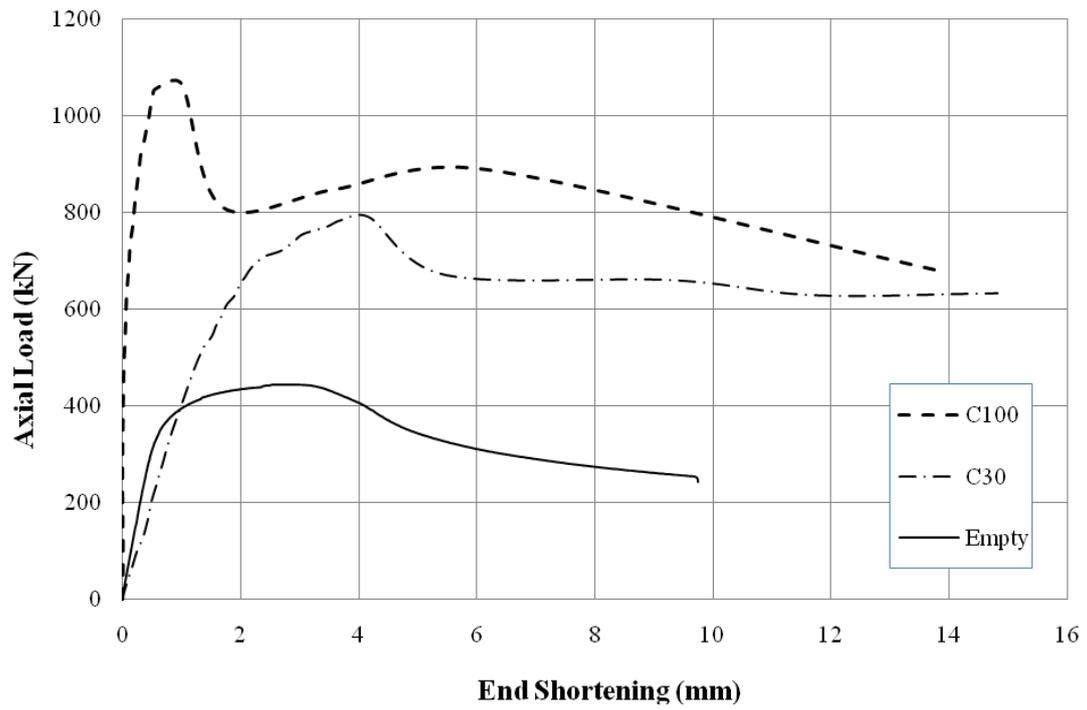


Figure 7: Axial load versus end shortening curves for EHS 121×76×3 composite columns

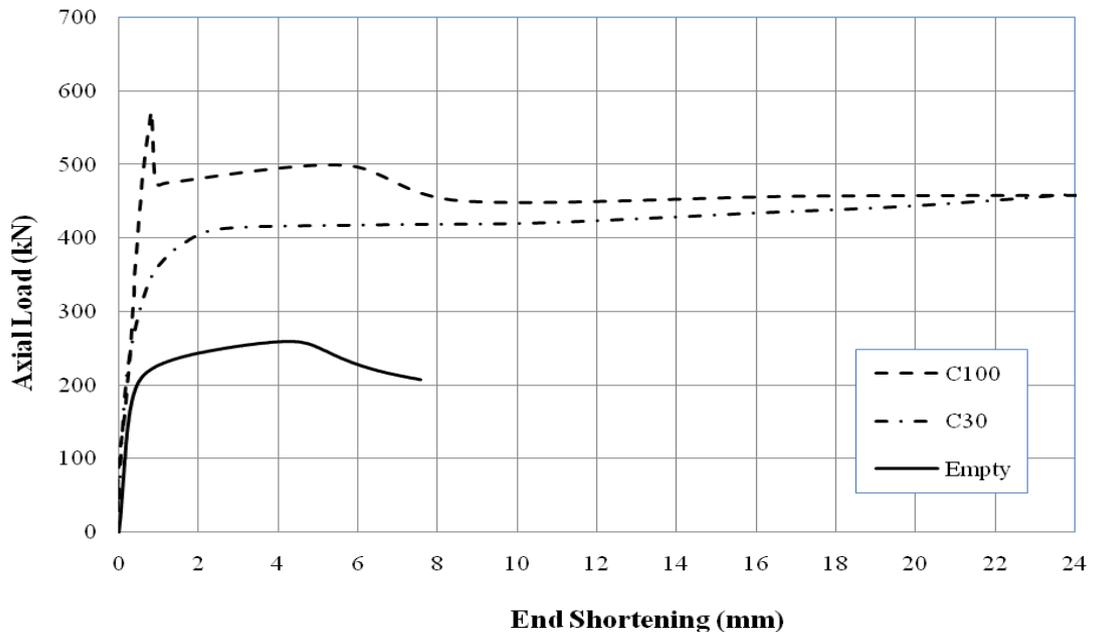


Figure 8: Axial load versus end shortening curves for EHS 86×58×3 composite columns

## DEVELOPMENT OF DESIGN RULES

Concrete-filled elliptical hollow sections are not explicitly covered by current design codes. The test results obtained in the present study are compared with existing design guidance for the circular concrete-filled tubes. Comparisons are made with EN 1994-1-1 (2004), abbreviated as EC4, in this paper. EC4 covers concrete-filled circular hollow sections with and without reinforcement. The compressive resistance  $N_{u,EC4}$  of concrete-filled steel tubes is given by Eq. (1), which takes into account increases in concrete capacity due to the confinement provided by the steel tube. For the comparisons made in this paper, all partial safety factors have been set equal to unity and the material properties have been taken as their measured values. This enables direct comparison between the design models and test results.

The EC4 compressive design resistance of concrete-filled CHS columns  $N_{EC4,CHS}$  is given by Eq. (1) and takes account of the interaction between the steel and concrete elements through the two factors  $\eta_a$  and  $\eta_c$ .

$$N_{u,EC4} = A_s \eta_a f_y + A_c f_c \left[ 1 + \eta_c \left( \frac{t}{D} \right) \left( \frac{f_y}{f_c} \right) \right] \quad (1)$$

where,

$N_{u,EC4}$	Ultimate axial capacity of the composite column
$f_c$	Design compressive strength of the concrete
$f_y$	Yield strength of the steel tube
$D$	Outer diameter of the steel section
$t$	Thickness of steel tube
$\eta_c$	Coefficient of concrete confinement
$\eta_a$	Coefficient of steel confinement

$\eta_a$  and  $\eta_c$  are functions of the column slenderness, which, for pure compression are given by Eqs. (2) and (3) respectively. Other symbols are as defined for Eq. (1).

$$\eta_a = 0.25(3 + 2\bar{\lambda}) \quad (\text{but } \leq 1.0) \quad (2)$$

$$\eta_c = 4.9 - 18.5\bar{\lambda} + 17\bar{\lambda}^2 \quad (\text{but } \geq 0) \quad (3)$$

where  $\bar{\lambda}$  is the non-dimensional column slenderness defined as the square root of the ratio between the plastic cross-sectional resistance and elastic member buckling resistance. The composite stub columns examined in this study are all of low slenderness ( $\bar{\lambda} < 0.1$ ).

### ***Continuous Strength Method***

The Continuous Strength Method (CSM) is a new deformation-based design approach for stainless steel structures, whereby structural resistance is determined by means of a continuous relationship between cross-section slenderness and deformation capacity and a representative constitutive model.

The cross-section slenderness  $\beta$  is defined as  $\beta = \frac{1}{2} \left( \frac{D_e - t}{t} \right) \frac{\sigma_{0.2}}{E_0}$  for EHS, where  $D_e = 2a^2/b$  is the

equivalent diameter of the EHS. The corresponding normalised deformation capacity of the section  $\epsilon_{LB}/\epsilon_0$  is acquired by means of Eq. (4) for circular and elliptical hollow sections, where  $\epsilon_{LB}$  represents the local buckling strain of the section and  $\epsilon_0$  is the elastic strain at the material 0.2% proof stress, equal to  $\sigma_{0.2}/E$ .

$$\frac{\epsilon_{LB}}{\epsilon_0} = \frac{0.116}{\beta^{1.21+1.69\beta}} \quad (4)$$

The above relationships were derived on the basis of regression analyses through a series of stub column test results as described by Gardner (2008) and Ashraf *et al.* (2008). Once the deformation capacity of the section  $\epsilon_{LB}$  has been found, the corresponding local buckling stress  $\sigma_{LB}$  can be obtained from the stress – strain curve of the stainless steel material or using the compound Ramberg–Osgood model appropriate for the stainless steel. Figure 9 shows the stress versus axial shortening curves of the unfilled stub column tests. The compression resistance of an unfilled stainless steel elliptical hollow section is then given by Eq. (5). The comparison of the results of the unfilled stub column test and the calculated values using the continuous strength method is shown in Table 4.

$$N_{u,Unfilled} = A_s \sigma_{LB} \quad (5)$$

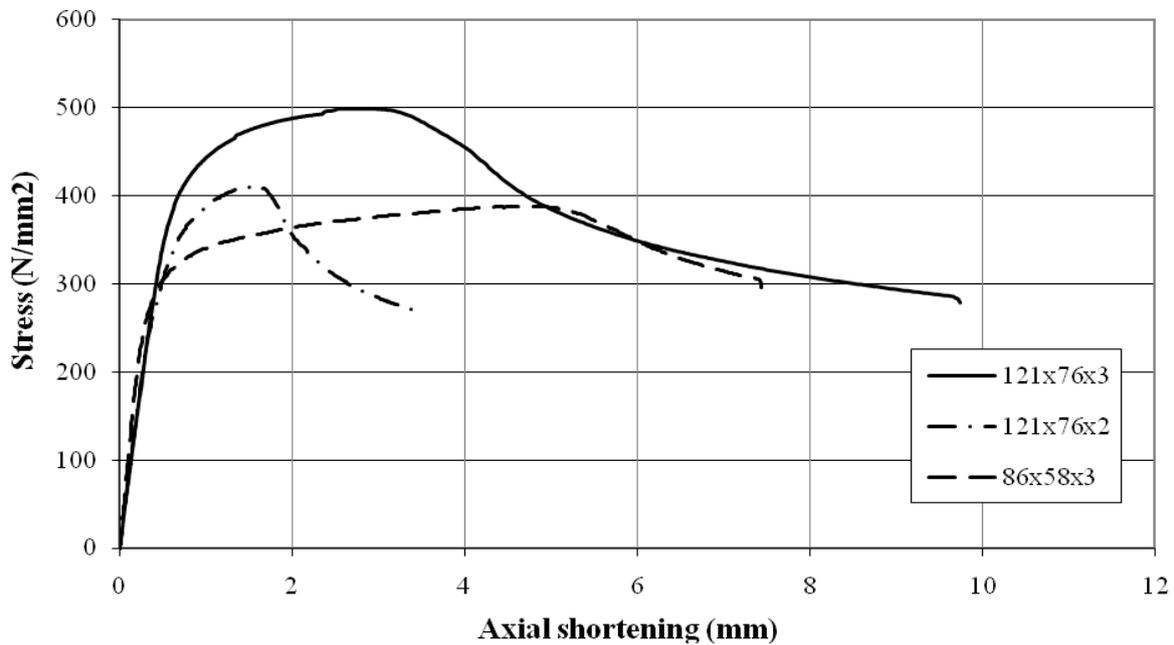


Figure 9: Stress versus axial shortening curves from the unfilled stub column tests

Table 4 Comparison of test results and calculated values for the unfilled stub columns

Specimen	$\epsilon_{LB}$	$\sigma_{LB}$ (N/mm <sup>2</sup> )	$\sigma_{Test}$ (N/mm <sup>2</sup> )
EHS 121×76×2	0.007024793	412.0	410.5
EHS 121×76×3	0.013308458	498.9	498.8
EHS 86×58×3	0.026631702	388.2	387.9

### Proposed Design Equation for Concrete-filled Stainless Steel EHS

It is proposed that the concept for evaluating the axial capacity of composite concrete-filled stainless steel circular hollow sections as described by Lam and Gardner (2008) could be extended to cover concrete-filled stainless steel elliptical hollow sections. To determine the contribution of the stainless steel tube to the resistance of the composite sections, the local buckling stress  $\sigma_{LB}$  was determined by applying the CSM as for circular sections (Gardner and Nethercot, 2004a; Lam and Gardner, 2008), but taking an equivalent diameter for the EHS as  $D_e = 2a^2/b$  (Chan and Gardner, 2008). The compressive resistance is defined for the concrete-filled stainless steel elliptical hollow section,  $N_{CSM,EHS}$  by Eq. (6):

$$N_{CSM,EHS} = A_s \eta_a \sigma_{LB} + A_c f_c \left[ 1 + \eta_c \left( \frac{t}{D_e} \right) \left( \frac{f_y}{f_c} \right) \right] \quad (6)$$

where,

$N_{CSM,EHS}$	Ultimate axial capacity of the concrete-filled stainless steel EHS
$f_c$	Design compressive strength of the concrete
$f_y$	Yield strength of the steel tube
$D_e$	Equivalent diameter of the elliptical hollow section
$t$	Thickness of steel tube
$\eta_c$	Coefficient of concrete confinement
$\eta_a$	Coefficient of steel confinement

The contribution of the stainless steel tube has been modified simply by replacing  $f_y$  in Eq. (1) by the local buckling strength  $\sigma_{LB}$ . It is proposed that the  $f_y$  (taken as the 0.2% proof strength of the stainless steel material) be maintained in the confinement term due to the fact that little confinement strength was provided by the steel section beyond yield. The ultimate loads achieved in the composite stub column tests performed in this study are summarised in Tables 5 and compared with the predicted resistances calculated from Eqs. (5) and (6). The measured geometric and material properties have been used in all predictions.

In this section, the test results presented herein are compared with proposed design rules. The proposed design equation is based on EC4 design rules for carbon steel concrete-filled circular columns and the new continuous strength method (CSM) recently devised for stainless steel concrete-filled hollow sections. For the comparisons made in this paper, all partial safety factors have been set equal to unity and the material properties have been taken as their measured values. This enables direct comparison between the design models and test results.

Table 5: Comparison of test results with proposed design model

Reference	$N_{u, Test}$ (kN)	$N_{u, CSM, EHS}$ (kN)	$\frac{N_{u, CSM, EHS}}{N_{u, Test}}$
EHS 121×76×2	233.6	234.4	1.00
EHS 121×76×3	443.9	443.9	1.00
EHS 86×58×3	258.8	259.0	1.00
EHS 121×76×2 – C30	551.2	526.3	0.95
EHS 121×76×3 – C30	792.4	725.8	0.92
EHS 86×58×3 – C30	412.3	407.7	0.99
EHS 121×76×2 – C100	856.7	879.8	1.03
EHS 121×76×3 – C100	1064.8	1064.0	1.00
EHS 86×58×3 – C100	570.0	576.3	1.01
		Mean	0.99
		SD	0.033

## CONCLUSIONS

A total of nine stub column tests have been performed to investigate the compressive behaviour of concrete-filled stainless steel elliptical hollow sections. Six of the specimens were concrete-filled while three were comparative unfilled sections. The compressive response was found to be sensitive to both steel tube thickness and concrete strength, with higher tube thickness resulting in higher load-carrying capacity and enhanced ductility, and higher concrete strengths improving load-carrying capacity but reducing ductility. The experimental results from the present study were compared with a proposed design equation which is based on the Eurocode 4 provisions for circular hollow sections and the continuous strength method for stainless steel sections. From the comparisons, it can be concluded that the proposed design rules for concrete-filled stainless steel EHS can be safely applied; further experimental studies on this new form of section are on-going.

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