Finite element analysis of concrete filled lean duplex stainless steel columns

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Abstract

In recent years, a new low nickel content stainless steel (EN 1.4162) commonly referred as 'lean duplex stainless steel' has been developed, which has over two times the tensile strength of the more familiar austenitic stainless steel but at approximately half the cost. This paper presents the finite element analysis of concrete filled lean duplex stainless steel columns subjected to concentric axial compression. To predict the performance of this form of concrete filled composite columns, a finite element model was developed and finite element analyses were conducted. The finite element model was validated through comparisons of the results obtained from the experimental study. A parametric study was conducted to examine the effect of various parameters such as section size, wall thickness, infill concrete strength, etc. on the overall behaviour and compressive resistance of this form of composite columns. Through both experimental and numerical studies, the merits of using lean duplex stainless steel hollow sections in concrete filled composite columns were highlighted. In addition, a new formula based on the Eurocode 4 was proposed to predict the cross-section capacity of the concrete filled lean duplex stainless steel composite columns subjected to axial compression.

Keywords: *Lean duplex stainless steel, composite columns, axial compression, finite element model, cross-section capacity, Eurocode 4*

1. Introduction

Concrete filled steel tubes (CFSTs) have been used for high-rise buildings and bridges throughout the world. This increase is due to their advantages in constructability and superiority in strength. CFST columns consist of steel and concrete materials acting together contributed to the higher stiffness and load bearing capacity of these columns [1].

Austenitic stainless steel is most widely used in the construction industry, however, a recently developed 'lean duplex' stainless steel which contains only 1.5% nickel offers a cheaper alternative. The particular grade used in this study is EN 1.4162, which is generally less expensive than the austenitic counterpart but offers higher strength, while maintaining a reasonable corrosion resistance. Numerous examples of lean duplex used in the construction could be found. Theofanous and Gardner [2] carried out experimental and numerical studies on the behaviour of lean duplex stainless steel square hollow sections (SHS) and rectangular hollow sections (RHS) subjected to axial compression, to investigate the effects of the sectional shape and wall thickness to the ultimate axial capacity. It was found that lean duplex sections offer superior strength when comparing to the austenitic counterparts, which in turn, provided a significant saving to the material cost.

Huang and Young [3] conducted finite element analysis (FEA) on cold-formed lean duplex stainless steel with square and rectangular hollow sections. An accurate finite element model has been created to simulate the pin-ended cold-formed lean duplex stainless steel short columns. The results showed that Eurocode 3 [4] and the Australian / New Zealand Standard [5] are relatively conservative in predicting the axial capacity of these form of hollow sections. Even though a significant number of researchers had conducted research on the lean duplex stainless steel sections, there is little research had been carried out on CFST columns with lean duplex stainless steel tubes.

Lam and Giakoumelis [6] evaluated CFST columns under a variety of loading conditions with load applied: 1) on the steel and concrete simultaneously, 2) on the concrete alone and 3) on the concrete and steel with greased interface. The steel grades of S275 and S355 were used and the concrete strength varied from 30 to 100 MPa. Results have shown that when the concrete and steel were loaded concurrently, the tube provided less confinement by comparison to the specimens that were only loaded to the concrete core, similar findings are also reported by Sakino *et al*. [7].

Studies on concrete filled carbon steel rectangular hollow section (RHS) composite columns have shown that width to thickness ratio of the steel elements and the constraining factor have significant influence to the compressive axial capacity and ductility of the concrete filled columns [8-13]. Research into CFST columns with high strength concrete infill has shown that high strength concrete infill provided enhancement in strength but led to reduction in ductility [14-16]. In terms of concrete filled composite columns with stainless steel sections, Uy *et al*. [17] tested 72 stub and 24 slender concrete filled stainless steel columns, with concrete strength varied from 20 to 75 MPa, results on the stub column tests have shown that CFST with stainless steel tube has higher residual strength and ductile behaviour when compared to the carbon steel counterpart. An investigation into the behaviour of circular concrete filled lean duplex stainless steel tube using the finite element package ABAQUS [18] was reported by Hassanein *et al*. [19]. However, the FE model was validated using experimental studies on austenitic stainless steel columns carried out by Chang *et al*. [20] and the behaviour especially at the section capacity is quite different. It can be seen that previous research into lean duplex composite columns is relatively limited, little experimental study has been made on concrete filled composite columns with lean duplex stainless steel sections. In the present study, a finite element model was developed and validated against the stub column experiments conducted by Lam *et al.* [21]. Parametric studies were carried out over a range of concrete grades and steel thicknesses.

The results of the parametric studies were used and compared with the existing design rule given in Eurocode 4 [22]. On the basis of the comparison, a new design expression based on the Eurocode 4 was proposed.

2. Summary of stub column tests

An experimental investigation was performed to assess the behaviour and response of concrete filled lean duplex stainless steel (EN 1.4162) square hollow sections subjected to axial compression. A total of nine stub column specimens were tested with various concrete strengths and sectional geometry. All the stainless steel sections used were cold-formed and seam-welded.

Measured dimensions of the specimens are summarized in Table 1, where t_f, t_c denote the wall thickness at flat and corner portions of the square hollow section. Average tested concrete cube strength was 35.1 MPa, 61.2 MPa and 81.0 MPa for the C30, C60 and C80 concrete specified in Table 1, respectively. SC1, SC2 and SC3 refer to square columns with steel tube dimensions of 60×60×3, 80×80×4 and 100×100×4 (unit: mm), respectively. Measured stainless steel properties are given in Table 2.

*Table 1.*Summarized measured stub column specimen's geometries. (mm)

Column ID	**Width, B**	**Height, H**	**Flat thk, t_f**	**Corner thk, t_c**	**Length, L**
SC1-C30	60.18	60.49	3.34	3.47	183.5
SC1-C60	59.96	60.34	3.41	3.68	184.5
SC1-C80	59.90	60.27	3.12	3.56	184.5
SC2-C30	80.27	80.16	3.82	4.19	243.5
SC2-C60	80.30	80.10	3.86	3.94	244.5
SC2-C80	80.19	80.42	3.73	4.05	244.5
SC3-C30	102.68	102.72	4.26	4.47	304.5
SC3-C60	102.93	102.52	3.99	4.42	304.5
SC3-C80	102.85	102.60	4.05	4.47	305.0

Table 2. Measured steel material properties.

Section	E_0 **(MPa)**	$\sigma_{0.2}$ **(MPa)**	$\sigma_{1.0}$ **(MPa)**	σ_u **(MPa)**	ε_f **(%)**
$S1_{flat}$	209800	755	819	839	44
$S1_{corner}$	212400	885	1024	1026	22
$S2_{flat}$	199900	679	736	773	42
$S2_{corner}$	210000	731	942	959	24
$S3_{flat}$	198800	586	632	761	47
$S3_{corner}$	206000	811	912	917	32

High strength mortar was applied to the top end of the concrete-filled stub columns and allowed to harden before testing, to achieve an even and uniform loading surface. Three linear variable displacement transducers (LVDTs) were installed in a triangular position on plan to measure the shortening of the column, two LVDTs were placed in the front of the column and one at the rear, so that any rotation and tilt of the column could be detected. Four strain gauges were attached to the four faces of the square stainless steel section at mid-height, two of them measuring the longitudinal strain whereas the other two measuring the hoop strain of the section. All the data collected by the instrumentations was automatically recorded by the data logging system. Test setup is illustrated in Fig. 1.

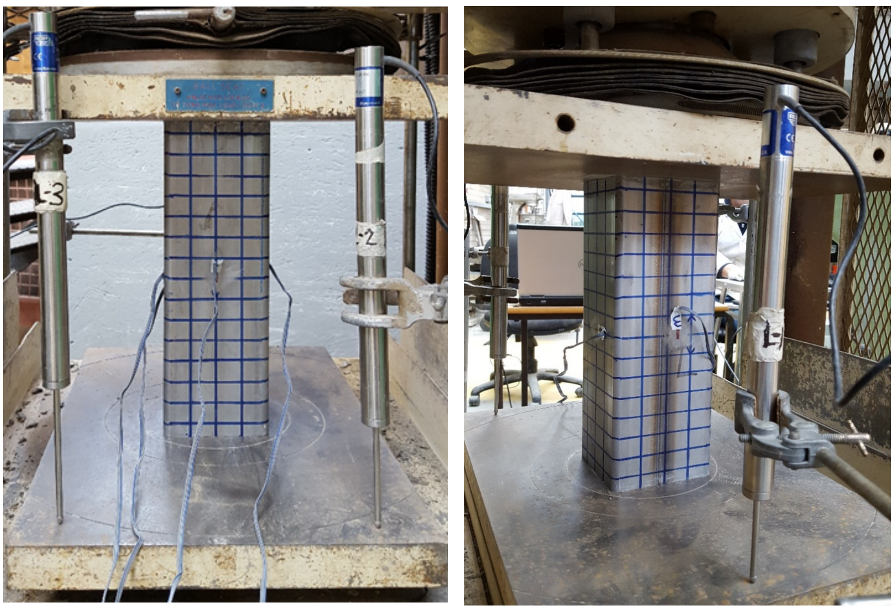


Fig. 1. Test setup for the stub column tests.

The column specimens were subjected to concentric axial compression. The load was applied using a 2500 kN capacity Avery Denison machine. Each specimen was loaded at 50 kN intervals at the beginning of the test (i.e. in the elastic region) and at a loading rate of 10 kN intervals after the column began to yield, in order to have sufficient data points to delineate the 'knee' of the load vs. axial shortening curve.

All the readings were recorded when both load and strain had been stabilised. After the immediate drop of the load due to local buckling, the test continued as the load stabilised until the load started again to increase slightly when the testing ended. Then the specimen was removed and carefully examined after the test.

The compressive load vs. axial shortening curves, typical failure mode and the maximum compressive load of the concrete filled lean duplex stainless steel columns obtained from the experiments will be illustrated in the following section for their comparison with the corresponding numerical results. The experimental results clearly identified the superior ductility of the lean duplex stainless steel sections; no corner cracking or splitting was observed in any of the test specimens.

3. Finite element model

3.1. General

The finite element package ABAQUS 6.14 (RIKS method) was used to simulate the concrete filled lean duplex stainless steel stub column tests summarized in the previous section. Geometry of the columns, materials, interactions, meshes, loading and boundary conditions of the FE model are defined accordingly and are described in the following sections.

3.2. Steel material

The stress-strain model used for both the flat and corner regions of the lean duplex stainless steel tube in the FE model included two parts. The first part is linear and up to the proportional limit stress with the measured elastic modulus E_0 (Poisson's ratio 0.3). The second part is a converted true stress-strain curve based on tested data, e.g. 0.2% ($\sigma_{0.2}$), 1% proof stresses ($\sigma_{1.0}$), the ultimate stress (σ_u) and the strain at fracture (ε_f) by using Eqs. (1) and (2).

$$\sigma_{true} = \sigma_{nom}(1 + \varepsilon_{nom}) \tag{1}$$

$$\varepsilon_{ln}^{pl} = \ln(1 + \varepsilon_{nom}) - \frac{\sigma_{true}}{E} \tag{2}$$

where σ_{true} and σ_{nom} represent the true and engineering stress, respectively, and ε_{ln}^{pl} and ε_{nom} are the logarithmic plastic strain and engineering strain, respectively. The corner properties were extended to a distance of two times of the tube thickness beyond the curved portions of the stainless steel cross-sections, as suggested by Gardner and Nethercot [23].

3.3. Concrete material

Available empirical models for confined concrete such as those presented in references [16, 24-25] have been proven to be acceptable to predict the behaviour of concrete-filled tubular columns with circular, square and elliptical steel hollow sections. In this study, the material model for concrete described in the following paragraphs was found to be most suitable to replicate the experimental results obtained from the compressive tests on lean duplex stainless steel stub columns.

The Drucker–Prager model available in ABAQUS material library was adopted to simulate the behaviour of concrete core. A three-part constitutive model was used to define the material. The first part was assumed as an elastic part up to the proportional limit which was defined as $0.5f_c$ (concrete cylinder strength, assumed as 0.8 times of the cube strength). The initial modulus of elasticity E_c was calculated by the empirical equation ACI Committee 318 [26] as given in Eq. (3). Poisson's ratio of concrete was taken as 0.2. The corresponding strain (ε_c) was taken as 0.003 [26].

$$E_c = 4700\sqrt{f_c} \qquad (3)$$

The second part started from the proportional limit stress ($0.5f_c$) to the concrete strength (f_c). The equation proposed by Saenz [27] was adopted shown as follows (Eq. 4).

$$f = E_c\varepsilon \Big/ \left[1 + (R + R_E - 2)\left(\frac{\varepsilon}{\varepsilon_c}\right) - 2(2R-1)\left(\frac{\varepsilon}{\varepsilon_c}\right)^2 + R\left(\frac{\varepsilon}{\varepsilon_c}\right)^3\right] \qquad (4)$$

where $R_E = \frac{E_c\varepsilon_c}{f_c}$, $R = \frac{R_E(R_\sigma - 1)}{(R_\varepsilon - 1)^2} - \frac{1}{R_\varepsilon}$, $R_\sigma = R_\varepsilon = 4$ [28].

The third part is linear and started from f_c to rkf_c whereas the corresponding strain is $11\varepsilon_c$. The value of r was taken as 1.0 and 0.5 for concrete with cube strength of 30 MPa and 100 MPa, respectively, whereas linear interpolation was used for cube strength between 30 and 100 MPa [16]. The value of k was calculated from an empirical equation given by Hu *et al*. [29] in Eq. (5).

$$k = 0.000178\left(\frac{B}{T}\right)^2 - 0.02492\left(\frac{B}{T}\right) + 1.2722 \quad \text{for } 17 \ll B/T \ll 70 \qquad (5)$$

3.4. Meshes and interfaces

Three-dimensional 8-node solid elements (C3D8) were employed to discretize the concrete-filled square stainless steel stub column models. Generally, a mesh size equals to the tube wall thickness was adopted in the flat portions of the steel columns, whereas minimum of 3 elements along curvature was used at corners. For concrete core, a mesh size of two times of the wall thickness was used. Two layers of meshes were used in the direction of the wall thickness.

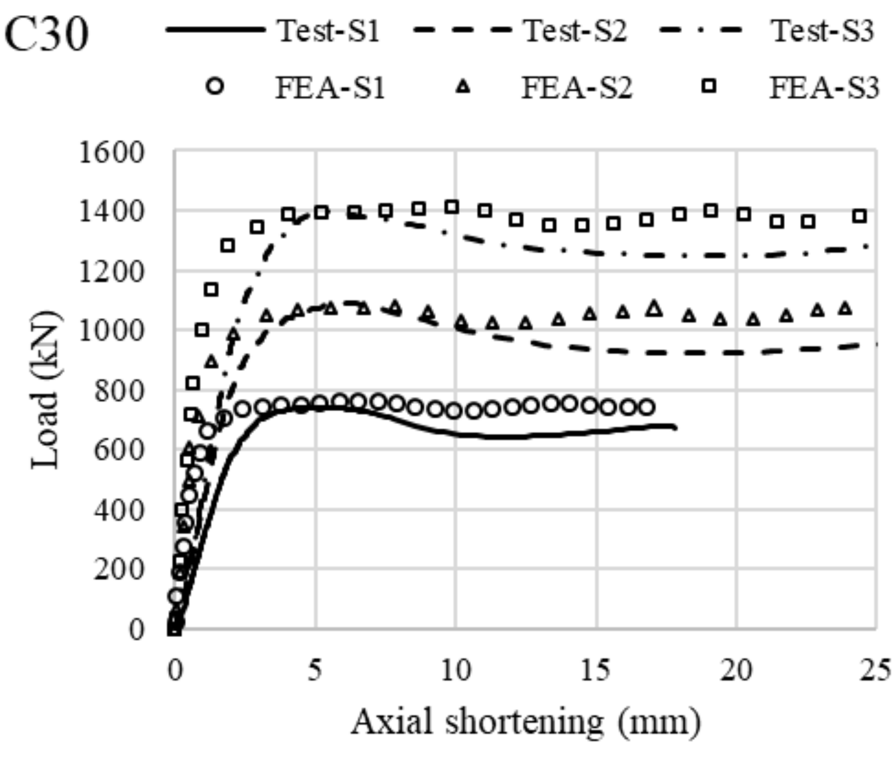
A surface-to-surface based interaction was adopted for the contact between steel tube (slave surface) and concrete core (master surface). In the direction tangential to the surface, the 'penalty' friction with a coefficient of friction equal to 0.3 was used, whereas 'hard contact' was used for the normal direction. End plates were included in the model to replicate the tests. The concrete was treated as slave surface in the interactions with the end plates.

3.5. Loading and boundary conditions

Load was applied axially through a reference point coupled to the top end plate by displacement control method. Both ends of the stub columns were restrained against all degrees of freedom, except for the displacement in the loading direction at the top. To reduce the calculation cost, a quarter model was simulated with symmetry boundaries in two directions.

4. Validation of the FE model

The FE model was validated with the load vs. displacement curves, ultimate capacities and failure modes of the concrete-filled lean duplex stainless steel columns tested. The comparison of the test and FEA curves is given in Fig. 2. Good agreement was achieved in terms of the overall relationship between the axial compressive load and the shortening of the columns.



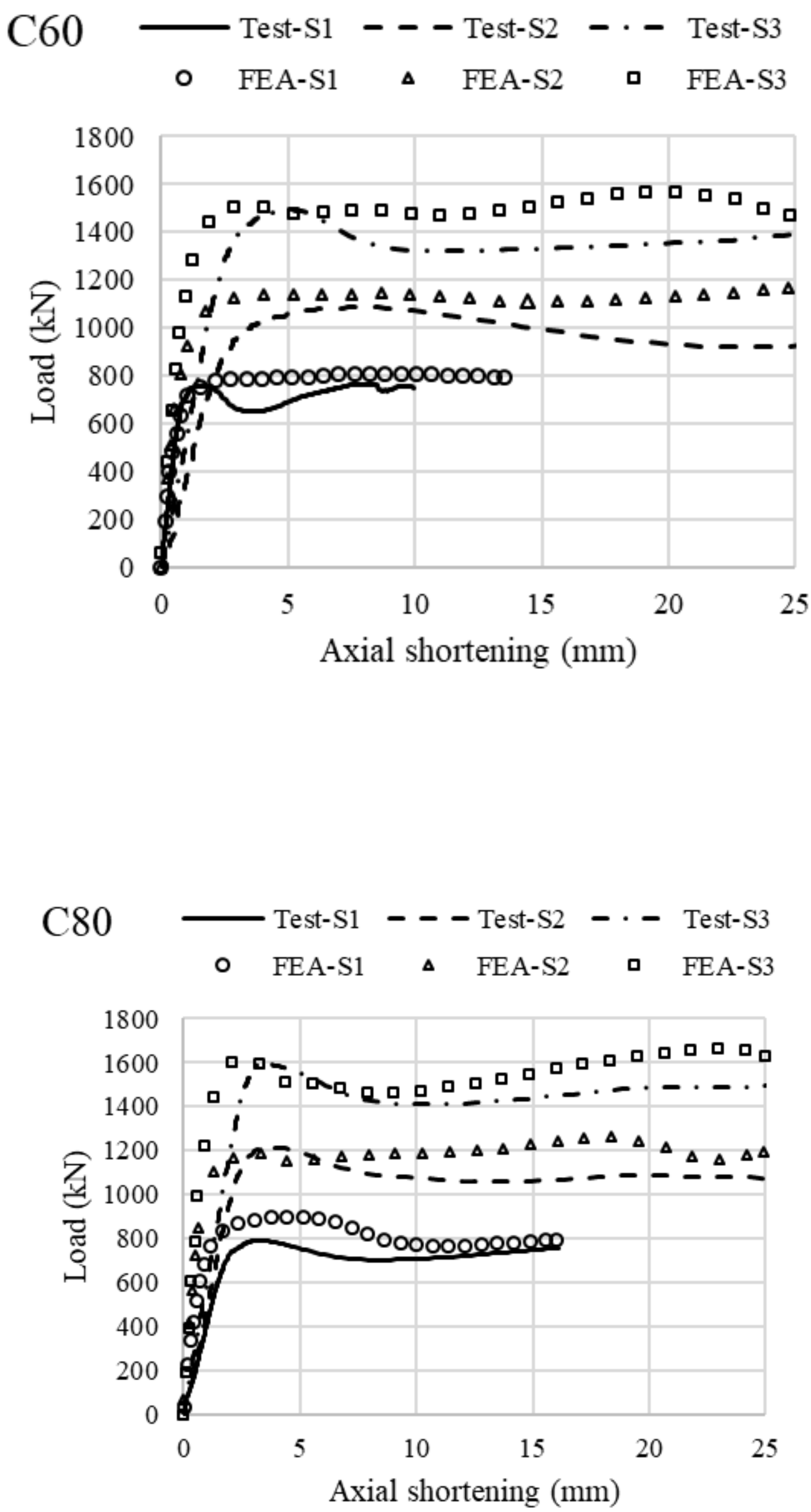


Fig. 2. Comparisons of load vs. displacement curves between test and FEA.

The column capacities recorded from the tests and extracted from the FEA is compared in Table 3. The average ratio of capacities N_{Test}/N_{FEA} is 0.98, with the standard deviation of 0.04 and the coefficient of variation (COV) of 0.044. The value of N_{Test}/N_{FEA} ranges from 0.88 to 1.02, within a satisfactory error of 12%. The failure modes observed from tests and predicted from FEA are shown in Fig. 3. It can be seen from the failure shapes and mode of failure (outwards local buckling), acceptable agreement was achieved. Based on the above comparison, the developed FE model is deemed to be capable of predicting both the ultimate compressive capacities and failure mode of the tested concrete-filled lean duplex stainless steel stub columns.

*Table 3.*Comparison of test and FEA results.

Column ID	N_{Test} **(kN)**	N_{FEA} **(kN)**	N_{Test}/N_{FEA}
SC1-C30	739	761	0.97
SC1-C60	759	808	0.94
SC1-C80	790	898	0.88
SC2-C30	1105	1079	1.02
SC2-C60	1160	1143	1.01
SC2-C80	1220	1193	1.02
SC3-C30	1394	1414	0.99
SC3-C60	1493	1519	0.98
SC3-C80	1599	1614	0.99
		Average	0.98
		Standard Deviation	0.04
		Coefficient of Variation	0.044

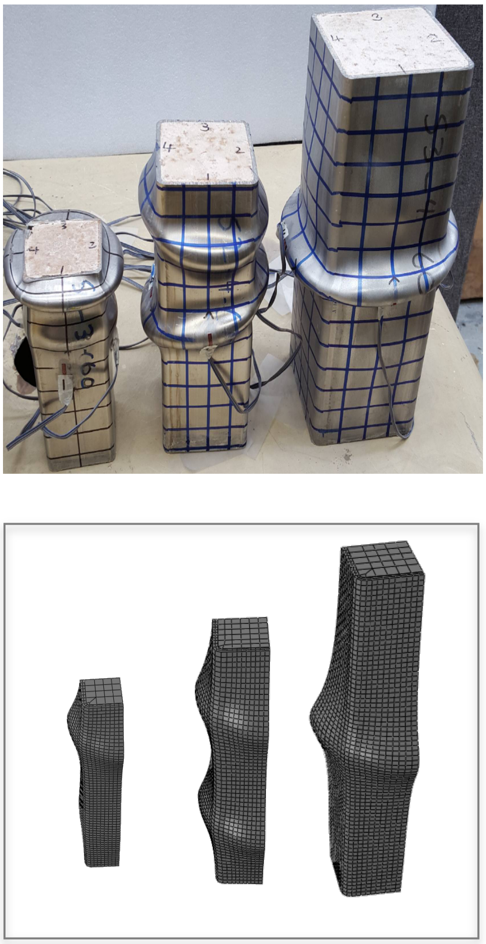


Fig. 3. Local buckling observed in both test and FEA results.

5. Parametric study

A preliminary parametric study was carried out employing the validated FE model. A total of 24 stub column models were considered to assess the effect of concrete cylinder strength and steel tube cross-sectional geometry on the axial compressive strength of the concrete-filled lean duplex stainless steel stub columns.

Table 4 summarizes the characteristics of the models. Overall 8 cross-sections were selected for the stainless steel tubes, ranging from 60×60×3 to 150×150×5, among which the ratio of the outer width to tube wall thickness (B/t_f) varied from 20 to 40. The length of all the stub columns was set to be $3B$. Adopted concrete cylinder strength was 30 MPa, 60 MPa and 80 MPa for each cross-section. In the parametric study, steel properties given in Table 2 for S1, S2 and S3 were used for cross-sections

60×60×3, 80×80×4 and 100×100×4, respectively. The properties of S1 were also used for cross-sections 100×100×3 and 120×120×3, and S3 for 120×120×4 and 150×150×5.

The axial compressive capacities of the considered columns extracted from the parametric study are given in Table 2 and are compared to the calculated results based on the design equation, Eq. (6), provided in Eurocode 4 for concrete-filled carbon steel tube columns.

$$N_{EC4} = A_s f_y + A_c f_{ck} \tag{6}$$

where

A_s is the cross section area of the steel section;

f_y is the yield stress of the steel section;

A_c is the cross section area of the concrete;

f_{ck} is the cylinder strength of the concrete.

Table 4. Details of concrete-filled lean duplex stainless steel stub columns considered in the parametric study.

Model ID	Concrete Grade	B/t_f	N_{sc} (kN)
60×60×3	C30	20	682
60×60×3	C60	20	748
60×60×3	C80	20	784
80×80×4	C30	20	1114
80×80×4	C60	20	1231
80×80×4	C80	20	1299
100×100×3	C30	33.3	1217
100×100×3	C60	33.3	1443
100×100×3	C80	33.3	1601
100×100×4	C30	25	1306
100×100×4	C60	25	1500
100×100×4	C80	25	1634
100×100×5	C30	20	1593
100×100×5	C60	20	1818
100×100×5	C80	20	1970
120×120×3	C30	40	1472
120×120×3	C60	40	1837
120×120×3	C80	40	2087
120×120×3	C30	40	1606
120×120×3	C60	40	1937
120×120×3	C80	40	2170
150×150×5	C30	30	2510
150×150×5	C60	30	3027
150×150×5	C80	30	3390

The comparisons for all the considered columns are illustrated in Fig. 4. The axial capacities of the composite columns are normalised using the current Eurocode 4 equation for concrete filled carbon steel tube columns, Eq. (6). The results showed that the current equation underestimated the axial capacities of the composite columns with lean duplex stainless steel sections. However, this is less noticeable for stainless steel sections with bigger B/t_f ratios and higher grade of concrete infill (for example 120×120×3 - C80), i.e. lesser confinement effect from the lean duplex stainless steel tube.

When the section size was maintained, the sections with a smaller B/t_f ratio had more significant increases to the capacities and a higher confinement effect to the concrete infill. However, the enhancement decreases with the increases of the concrete cylinder strength, as shown by the square solid data points (for sections 100×100). The sections with the same B/t_f ratio and concrete strength showed having similar enhancement on the axial capacities despite the different in section sizes.

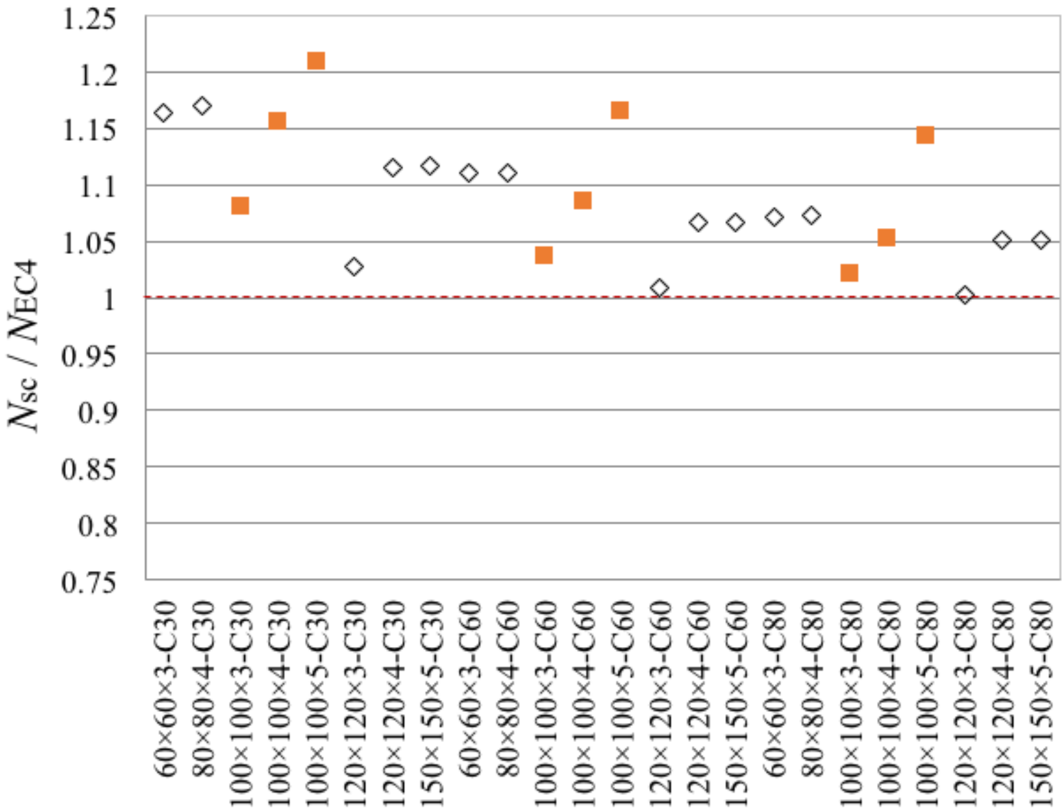


Fig. 4. Comparison of axial capacities (parametric results vs. EC4)

6. Prediction of axial capacity

To provide a better prediction of the axial compressive capacity of concrete-filled lean duplex stainless steel columns, Eq. (7) was proposed based on Eq. (6) and is given as follows,

$$N_{prop} = A_s \sigma_{1.0} + \varphi A_c f_{ck} \quad (7)$$

where

$\sigma_{1.0}$ is the steel strength at 1.0% strain;

φ is the confinement coefficient for the infilled concrete.

In this study, the confinement coefficient (φ) for the concrete infill is taken as 1.1 for simplicity. Table 5 shows the comparison of the parametric results vs. the results calculated from the new proposed design equation. The average ratio of capacities N_{sc}/N_{prop} is equalled to 1.00, with the standard deviation of 0.053 and COV of 0.053. The average value of (for each cross-section with different concrete strengths) N_{sc}/N_{prop} ranges from 0.92 to 1.12, within a satisfactory average error of 12%. Comparisons of the axial capacities are shown in Fig. 5.

*Table 5.*Comparison of parametric results vs. proposed design equation.

Model ID	***Concrete Grade***	**N_{sc} (kN)**	***N_{prop} (kN)***	***N_{sc}/N_{prop}***
60×60×3	C30	682	637	1.07
60×60×3	C60	748	733	1.02
60×60×3	C80	784	797	0.98
80×80×4	C30	1114	1035	1.08
80×80×4	C60	1231	1206	1.02
80×80×4	C80	1299	1320	0.98
100×100×3	C30	1217	1226	0.99
100×100×3	C60	1443	1517	0.95
100×100×3	C80	1601	1711	0.93
100×100×4	C30	1306	1224	1.07
100×100×4	C60	1500	1502	1.00
100×100×4	C80	1634	1688	0.97
100×100×5	C30	1593	1427	1.12
100×100×5	C60	1818	1693	1.07
100×100×5	C80	1970	1871	1.05
120×120×3	C30	1472	1559	0.94
120×120×3	C60	1837	1988	0.92
120×120×3	C80	2087	2274	0.92
120×120×4	C30	1606	1560	1.03
120×120×4	C60	1937	1974	0.98
120×120×4	C80	2170	2250	0.96
150×150×5	C30	2510	2438	1.03
150×150×5	C60	3027	3084	0.98
150×150×5	C80	3390	3515	0.96
			Average	1.00
			Standard Deviation	0.053
			Coefficient of Variation	0.053

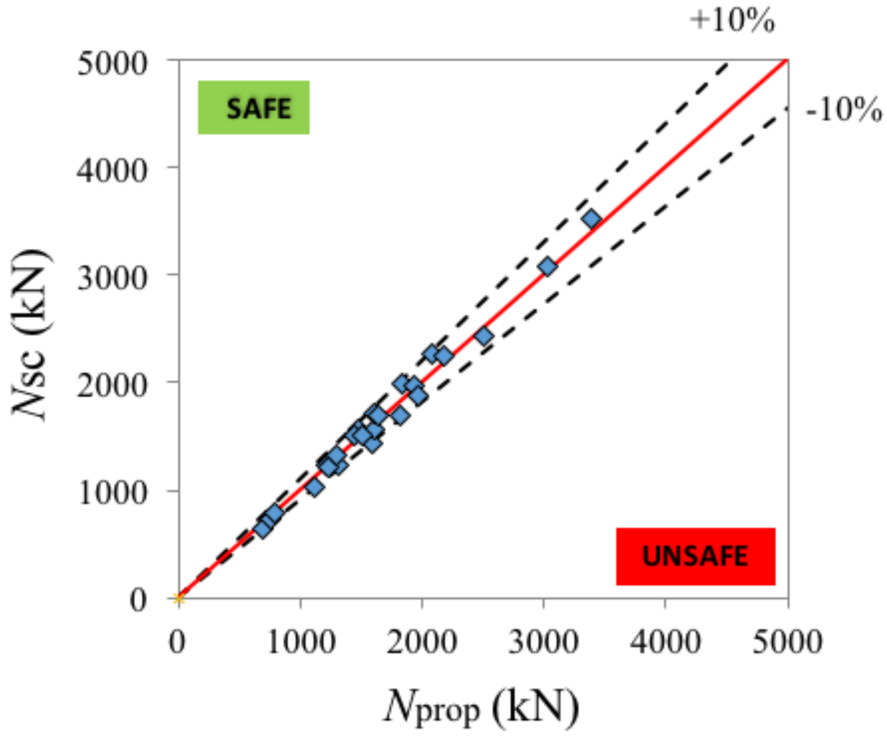


Fig. 5. Comparison of axial capacities (parametric results vs. proposed equation)

7. Conclusions

Investigations on the structural performance of concrete filled lean duplex stainless steel columns subjected to concentric axial compressive load were presented in this paper. A finite element model was developed and validated by using the results obtained from the experimental study. A parametric study was then carried out to examine the effect of concrete cylinder strength and sectional geometry on the compressive capacity of the composite columns. Through both experimental and numerical studies, the merits of using lean duplex stainless steel hollow sections in concrete filled composite columns were highlighted. A new formula based on the Eurocode 4 was proposed to predict the cross-section capacity of the concrete filled lean duplex stainless steel composite columns subjected to axial compression. The results showed that the proposed equation could provide an acceptable prediction on the axial capacity of the concrete filled lean duplex stainless steel columns investigated.

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