Parametric Study of Concrete Filled Fabricated Steel Box Composite Column

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Abstract. Concrete-filled fabricated steel box composite columns, particularly concrete-filled box sections, are crucial in modern structural engineering due to their high load-carrying capacity, stiffness, and ductility. However, full-scale testing of composite columns is often impractical due to high costs and lack of test facilities, making computer-aided modeling an essential alternative. While extensive research has been conducted on composite columns, a comprehensive understanding of how multiple design parameters such as the B/t ratio, L/B ratio, and material strengths, together affect axial load-bearing capacity and overall buckling behavior. Moreover, limited studies exist comparing different international design codes' predictions of composite column behavior. This study addresses these gaps by conducting parametric analyses to evaluate the impact of plate thickness (B/t), high-to-width ratio (L/B), concrete and steel strength on load-bearing capacity and stability of composite columns. The geometry of the parametric columns was square, with sizes ranging from 300mm to 600mm, commonly used in civil engineering structures. Steel strength values of 250MPa, 345MPa, 415MPa, and 500MPa, and concrete strengths of 21MPa, 28MPa, 35MPa, and 41MPa were considered. The modulus of elasticity of steel was consider 200GPa and poison's ratio taken 0.3. Concrete modulus of elasticity was calculating from the relation of 4700√f'c and poison's ratio taken 0.2. The effects of B/t ratio were examined by changing the steel plate thickness, while L/B ratios were studied by altering column lengths from 3m to 6m. Finite element analysis using ANSYS Workbench was conducted to numerically verify analytical strength values derived from ACI, AISC, and EC4 design codes. A displacement-based axial compressive load was applied to evaluate the ultimate strength, ductile behavior, and failure modes of the columns. Results indicated that increasing steel and concrete strength, as well as plate thickness, significantly enhances axial capacity, while increasing L/B ratios reduced buckling capacity. The AISC code was found to be more conservative than other design codes. These findings contribute to the development of stronger, more efficient composite column designs for various engineering applications.

Keywords: Ultimate strength, Steel box section, B/t ratio, L/B ratio, Parametric study.

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1 Introduction

Concrete filled fabricated steel box composite columns, particularly concrete-filled box sections, represent a critical component in modern structural engineering due to their significant load-carrying capacity, stiffness, and ductility. By combining the advantages of steel and concrete, these composite columns offer enhanced structural efficiency and performance, making them ideal for various applications in high-rise buildings, bridges, and other structures subjected to heavy loads and seismic forces. Parametric studies play a pivotal role in understanding the influence of key design parameters on the properties and performance of concrete-filled steel box composite columns. These studies involve systematically varying parameters such as cross-sectional dimensions, material properties, and loading conditions to evaluate their impact on structural response. Composite Column are increasingly being used in all type buildings, bridges and other mega structures. The strength of the column depends on the steel and concrete materials' strength as well as other properties. Also, there are some parameters to calculate the fabricated steel box column strength like the dimension, slenderness ratio (L/B), width to thickness ratio (B/t) and the shape of the steel section (Box). In this study square shape fabricated built-up steel box section was considered. The materials strength variation along with the L/B ratio and B/t ratio, other parameters of the composite columns will be the same to observe the peak strength and ductility. The design of fabricated steel box composite columns is typically governed by building codes and engineering standards specific to each region. The different code specifies the material's strength limitations and design formulas for the concrete filled steel box composite column. AISC, ACI, EC4 had specific design equations for the design and calculation of concrete filled steel box composite column. Besides these, extensive research on the axial capacity of the fabricated steel box column is conducted. Fig. 1 shows the cross section of concrete-filled fabricated steel box composite column and hollow steel box section.

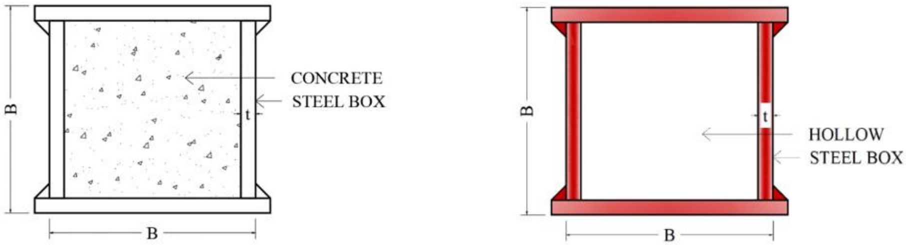


Fig. 1. Cross Section of Concrete Filled and hollow steel box column.

The properties of concrete-filled steel box composite column were studied with the finite element (FE) analysis [1]. The steel plate materials strength used Q345 and compressive strength of concrete used 46MPa. The FE model was conducted by ANSYS FEA software and the modeling used SOLID45 and SOLID65 element for modeling of steel and concrete materials. William-Warnke five parameters rule was used to check the cracked and crashed of concrete structure. The finite element analysis indicates that as the width-to-thickness ratio increases, both the strength increases factor of restrained concrete and the bearing capacity enhancement factor tend to decline. Steel yield strength of 235 MPa and ultimate strength of 375 MPa were utilized in computational research on concrete-filled double skin composite tube columns under axial compressive stress [2]. The compressive strength of concrete was 62.3MPa. FE analysis was carried out by ANSYS software, and eight-node SOLID45 element use to model steel materials and SOLID65 element was used for modeling of concrete materials. The failure of the specimen was observed due to failure of steel plate and from the numerical simulation it was observed that concrete crushing occurs due to steel box failure.

The properties of axially compressed high strength steel box columns was investigated using steel plate materials strength of 460MPa [3]. The bilinear perfect elastic-plastic model of ANSYS materials was used for numerical analysis. Maximum column strength influence by the initial geometric imperfection and Residual stresses. The verified finite element model was used to study how initial geometric imperfections and residual stresses affect the peak loading capacity of the columns. The cyclic parameter of eccentrically compressed steel box composite column using the repeated horizontal loading was conducted by numerical technique [4]. ANSYS finite element analysis software was used, and a 4-node Shell181 element was used to model the steel plate materials. The finite element analysis incorporates the influence of initial geometric imperfection. The numerical simulation results were well agreed with the experimental results.

Experimental and numerical studies were also conducted on the fire-exposed stainless-steel column filled with concrete [5]. The compressive strength of concrete used 41MPa to 46MPa and the maximum temperature used use 800°C. The ABAQUS finite element software was apply to analyze the thermal-stress. The model selects C3D8R element for modeling of concrete materials. The FE model result prediction the test results very well. A three-dimensional numerical analysis of concrete filled steel tubular column was conducted with the help of ANSYS finite element software. The numerical model was predicting the ultimate axial load carrying capacity of concrete filled short square steel tube column [6]. The 3D numerical model used eight-node SOLID 45 element for steel materials modeling and SOLID65 element used for concrete materials modeling. TARGE170 AND CONTA173 element was used to simulate the steel concrete interaction. In conclusion the FE model predicts the axial capacity of the columns.

Under eccentric loading, a numerical analysis was investigated for square concrete-filled double steel tubular short columns [7]. The yield strength of steel used 345MPa to 412MPa and concrete compressive strength used 19MPa to 20MPa. Effect of steel strength, effect of concrete strength, effect of local buckling and effect of axial load ratio observed on the column capacity. Numerical results show that increasing the B/t ratio significantly reduces the initial bending stiffness and the ultimate axial and bending resistance of concrete-filled double steel tubular columns.

The hysteretic characteristics of stainless-steel welded box-section columns and applied vertical and horizontal loads were investigated numerically [8]. ANSYS finite element software was employed for development of FE model and SHELL 181 element was used to model the stainless-steel materials. The multi-linear behavior of the materials with 20 intervals was used. Parametric study was conducted for validation of finite element models. The classification of welded box-section columns was the subject of a different study on box columns made of stainless steel [9].

An investigation on the seismic behavior through numerical analysis using ABAQUS finite element software, was investigated the plane frames with special- shaped concrete-filled steel tubular columns [10]. The numerical result was confirmed with test result. In conclusion the ABAQUS FE model is operative in pretending the seismic behavior of the column. A nonlinear numerical analysis was simulated and submit an equation for axial strength capacity of concrete field steel tube column with initial imperfection [11]. ANSYS v18 finite element software was used to model the steel tube column. The numerical model used SOLID65 and SOLID185 element for modeling of concrete and steel materials. A parametric study was shown to verify all numerical results and the finite element modeling show the efficient comparison against the experimental results.

2 Methodology

This study investigates the influence of the main parameters such as width-to-thickness ratio, Hight-to-width ratio, concrete and steel strength on the axil capacity and stability of concrete filled steel box composite columns. A total of sixteen columns, with sizes of 300 mm were selected for a parametric and numerical study. The columns are identified with four groups with group designation of G1, G2, G3 and G4 in Table 1. Each group contain four columns and all columns are square. Group G1 used different plate thicknesses of 6mm, 8mm, 10mm, and 12mm. Those plate thicknesses are denoted after the group number, for example G112 indicate group one with 12mm plate hollow steel box section. The variation of plate thickness affects the B/t ratios, where lower plate thickness defines higher B/t ratio and vice versa. Four columns were considered in group G2 (Table 1) having plate thickness of 12mm and the length of the columns were varied to het the different vales of L/B ratios with constant B/t ratio as 25. Different column heights were examined to observe axial strength at various height-to-width (L/B) ratios. The height-to-width ratio varies from 10 to 20 in group G2, considering the column section as compact and non-slender. The variation of materials strength was also a key parameter here and for this different strength steel and concrete was taken in to consider in group G3. The variable concrete strengths were taken to detect the effect of concrete strength. The different strength steel plate was used to observe the effect of steel strength in group G4, for this different strength of 250, 345, 415 and 500MPa steel were used in group G4 as shown in Table 1. Fig. 2 shows the cross-section of the parametric column specimen.

Fig. 2. Cross-section of parametric column specimen

Table 1. Geometric and materials parameters of specimens

SP ID	B (mm)	t (mm)	L (mm)	B/t	L/B	f'c (MPa)	fy (MPa)
G106	300	**6**	3000	**50**	10	21	250
G108	300	**8**	3000	**38**	10	21	250
G110	300	**10**	3000	**30**	10	21	250
G112	300	**12**	3000	**25**	10	21	250
G212L3	300	12	**3000**	25	**10**	21	250
G212L4	300	12	**4000**	25	**13**	21	250
G212L5	300	12	**5000**	25	**17**	21	250
G212L6	300	12	**6000**	25	**20**	21	250
G312C21	300	12	3000	25	10	**21**	250
G312C28	300	12	3000	25	10	**28**	250
G312C35	300	12	3000	25	10	**35**	250
G312C41	300	12	3000	25	10	**41**	250
G412S250	300	12	3000	25	10	21	**250**
G412S345	300	12	3000	25	10	21	**345**
G412S415	300	12	3000	25	10	21	**415**
G412S500	300	12	3000	25	10	21	**500**

The geometric and material parameters of all the sixteen Concrete filled fabricated steel box composite column specimens are tabulated in Table 1. The plate thickness changing from 6mm to 12mm, effects on B/t ratio from 25 to 50. Specimen lengths were selected 3m to 6m, leading to an L/B ratio that varied from 10 to 20. The study examined the effects of four different concrete strengths and steel strengths on the ultimate capacity of the columns. Numerical analysis was performed using ANSYS Workbench to simulate the behavior of these parametric columns. The material properties and dimensional parameters used in the numerical modeling were consistent with those of the parametric columns. Additionally, the boundary conditions and other numerical settings were maintained in alignment with the parametric columns. A buckling analysis was performed to identify the critical buckling load of the columns, and the numerical results were compared with the analytical values.

2.1 Codes and Standards

Numerous design codes worldwide provide the specifications and requirements of Concrete Filled Fabricated Steel Box Composite (CFFSBC) Columns. A comprehensive array of design provisions exists [12-13] including European standard (Euro code 4, 2004) and these standards offer guidelines and methodologies for the design and structural analysis of CFFSBCs. However, among the extensive selection of available provisions, ACI 318 (2014), AISC-LRFD (2016), and Euro code 4 (2004) take precedence, particularly in the realm of designing Steel-Concrete Composite Structures. These three standards are widely embraced and applied due to their comprehensive nature and specific directives concerning the axial load-bearing capacity of CFFSBCs. In subsequent sections, the specifications outlined within ACI 318 (2014), AISC-LRFD (2016), and Euro code 4 (2004) affecting to the axial capacity of concrete-filled fabricated steel box composite columns are detailed, highlighting their methodologies and critical considerations in structural design and analysis.

The American Institute of Steel Construction (AISC) provides the design equations for concrete-filled steel box composite columns in the AISC 360-16 "Specification for Structural Steel Buildings". The nominal axial capacity of a concrete-filled steel box composite column can be determined using the following equation:

$$P_n = P_{n0}\left[0.685^{\left(\frac{P_{n0}}{P_e}\right)}\right] \tag{1}$$

$$P_{n0} = \left[A_s f_y + A_{sr}\, f_{ysr} + 0.85\, f_{cu} A_c\right] \tag{2}$$

$$P_e = \pi^2 EI_{eff}/KL^2 \tag{3}$$

where,

A_c = Concrete area mm^2;
A_{sr} = Reinforcing bars area, mm^2;
A_s = Steel section area, mm^2;
EI_{eff} = Effective moment of inertia, Kip-mm^2;
f_{cu} = Minimum concrete compressive strength, MPa;
f_y = Steel yield stress, MPa;
f_{ysr} = Rebar yield stress, MPa;
K = Effective length factor;
L = Length of the member, mm.

2.2 Steel Plate Usages

The size of the parametric column used was 300 x 300 mm, resulting in a total gross area of 90,000mm^2. The areas for steel and concrete vary due to differences in plate thickness. For a 6mm plate, the calculated steel area is 3,564mm^2, which constitutes 3.96% of the gross area, representing the lowest percentage of steel used in the parametric columns. In contrast, for a maximum plate thickness of 12mm, the steel percentage increases to 7.84%, the highest in this study. Notably, these percentages exceed the minimum requirements specified by the codes, which stipulate a minimum steel percentage of 1% of the gross area.

2.3 Concrete Parameters

In the parametric study, the concrete parameters were based on brick aggregate concrete. The modulus of elasticity for this concrete calculated using the equation $3750\sqrt{f'c}$, as specified by [14]. The strength parameters varied from 21MPa to 41MPa and the poison ratio was taken 0.2. The numerical analysis utilized the same parameters to simulate all parametric columns.

3 Results and Discussions

3.1 Effect of B/t ratio

Width to thickness ratio (B/t) which is depends on the CFFSBC columns width and the wall thickness or plate thickness that use to fabricated the box section. Four plate thicknesses are used for the parametric study to keep the B/t ratios parameters within 25 to 50. Other parameters are keeping constant like L/B ratio, concrete and steel strength. The B/t ratios employed in four parametric columns in group G1 as shown in Table 2. The analytical capacity from different codes and numerical capacity from ANSYS software also explored in Table 2. The ultimate capacity of the specimen is calculated from equation 4, the results are defined by $P_{n,\ EC4}$. The effect of B/t ratio on the ultimate capacity of the column is explored in the axial capacity increased as shown in Table 2. The ultimate axial capacity of the CFFSBC column increase by 48% from changing the B/t ratio from 50 to 25. The $P_{num}/P_{n,EC4}$ ratio shows that the numerical simulation result is well matched with the ultimate capacity of all the specimen from Code provided equation. The load displacement curve is generated form the numerical result for different plate thickness shown in Fig. 3. From Table 2, it is observed that the increase of B/t ratio decrease the column axial strength. The lower B/t ratio observed in using higher plate thickness that increase the area steel in column and increase the axial strength of the column.

Table 2. Load Carrying Capacity of Specimens having different B/t ratios

SP ID	B mm	t mm	L mm	B/t	L/B	$P_{n,ACI}$ kN	$P_{n,AISC}$ kN	$P_{n,EC4}$ kN	P_{Num} kN	$P_{Num}/P_{n,EC4}$
G106	300	6	3000	50	10	3299	3149	3560	3618	1.02
G108	300	8	3000	38	10	3872	3706	4126	4145	1.00
G110	300	10	3000	30	10	4449	4265	4696	4718	1.00
G112	300	12	3000	25	10	5032	4825	5272	5295	1.00

The analytical capacity of the column is calculated form the equation

$$P_n, EC_4 = A_c f_c + A_s f_y + A_{sr} f_{yr} \tag{4}$$

Fig. 4 explores the load capacity curve of specimens having different B/t ratios obtained from Equation (4), ACI code and numerical analysis results. Fig. 4 shows that lower B/t ratio contribute higher axial capacity and it is also observed that the numerical results is very close to the analytical capacity, $P_{n,EC4}$. From ANSYS analysis, the typical directional deformation contour result is shown in Fig. 5 of the specimen G112.

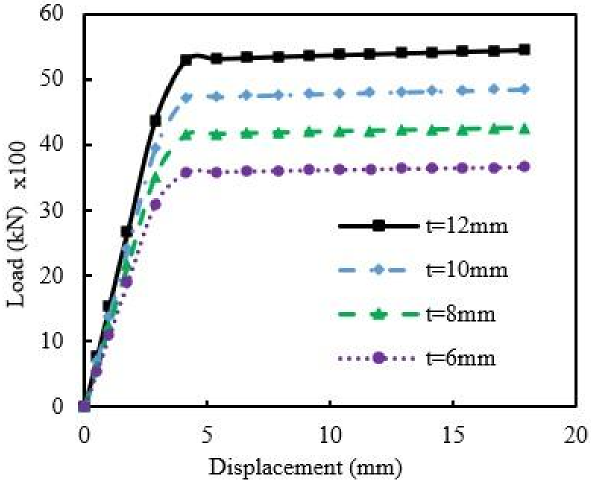


Fig. 3. Load displacement curve for different plate thickness

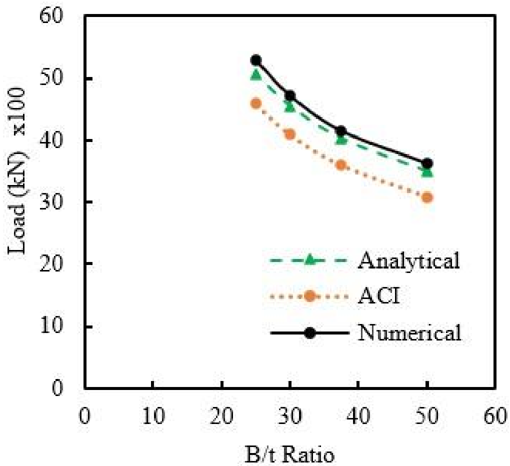


Fig. 4. Capacity curve for different B/t ratios

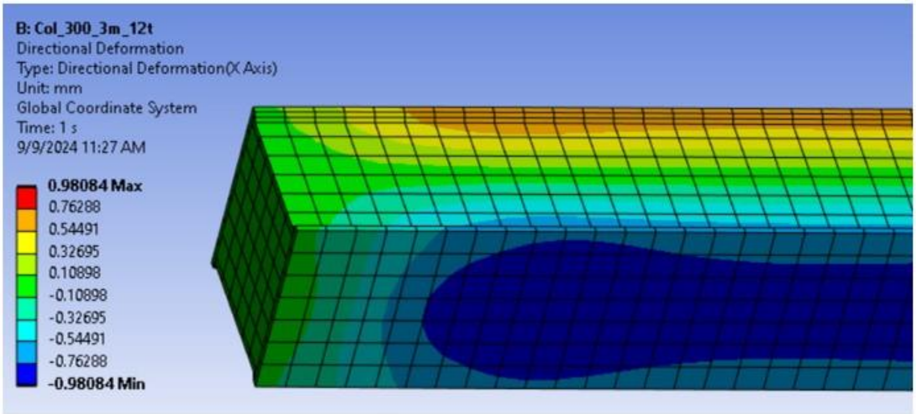


Fig. 5. Directional deformation of specimen G112

3.2 Effect of L/B ratio

The length of the column specimen was varied from 3m to 6m to observe the variation of the column axial strength. Variation of column length 'L' effects the L/B ratio parameters. ACI formulas was used to calculate the axial strength of the column for different L/B ratios. Fig. 6 explore the load-displacement curves of CFFSBC columns with variable L/B ratios for group G2. The ultimate capacity of the column is not varied because the effect of length is not included in code prescribed formulae. But there is a change of displacement, the maximum sectional capacity was in a same line but the displacement is changing, so this behavior indicates that the ductility of the column varies. Table 3 shows the ACI code analytical results and numerical results for static analysis. Numerical simulation results are observed little bit higher than that of ACI code analytical results because the numerical simulation used full materials strength. In ACI code a strength reduction factor was used.

Table 3. Capacity of Specimens having different L/B (Static Analysis)

SP ID	B (mm)	t (mm)	L (mm)	B/t	L/B	$P_{n,ACI}$ (kN)	P_{Num} (kN)	P_{Num}/P_{Ana}
G212L3	300	12	3000	25	10	5272	5295	1.00
G212L4	300	12	4000	25	13	5272	5293	1.00
G212L5	300	12	5000	25	17	5272	5293	1.00
G212L6	300	12	6000	25	20	5272	5290	1.00

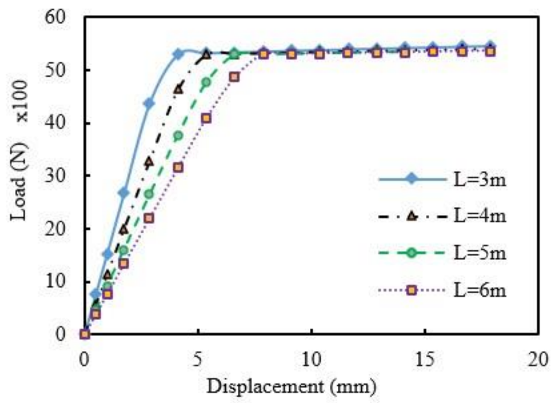


Fig. 6. Load displacement curve for different L/B ratios

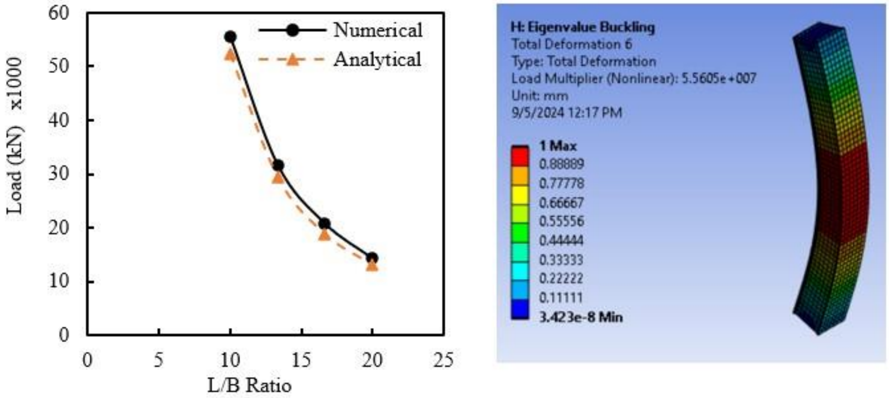
The buckling analysis was also conducted by the ANSYS WORKBENCH Eigen buckling analysis application. The column length was varied in group G2 and other parameters were remained constant. Table 4 shows the buckling analysis results for variation of L/B ratios. The relation between load capacity and L/B ratios is display in Fig. 7(a) whereas Fig. 7(b) describes the Eigen buckling behavior of a numerical model.

Table 4. Capacity of Specimens having different L/B (Buckling Analysis)

SP ID	B (mm)	t (mm)	L (mm)	B/t	L/B	$P_{e,ACI}$ (kN)	P_{Num} (kN)	P_{Num} / P_e
G212L3	300	12	3000	25	**10**	52345	**55605**	1.06
G212L4	300	12	4000	25	**13**	29444	31711	1.08
G212L5	300	12	5000	25	**17**	18844	20720	1.10
G212L6	300	12	6000	25	**20**	13072	14230	1.09

3.3 Effect of concrete strength (f′c)

The compressive strength of concrete is an important factor in the design and analysis of composite columns. Concrete strength is a one of the key parameters for the parametric study and effects an important part in increasing the strength of column. For composite columns, the compressive strength of the concrete plays a vital role in determining the load-bearing capacity and stability of the column. Composite columns combine concrete and steel, typically in the form of a steel section encased in concrete or a concrete-filled steel box (CFSB). This combination allows the column to take advantage of both materials, the compressive strength of concrete and the tensile strength and ductility of steel. Table 5 explores the results of concrete strength variation. Fig. 8(a) shows the numerical load displacement curve for different f′c and the capacity curve of different concrete strength is shown in Fig. 8(b).

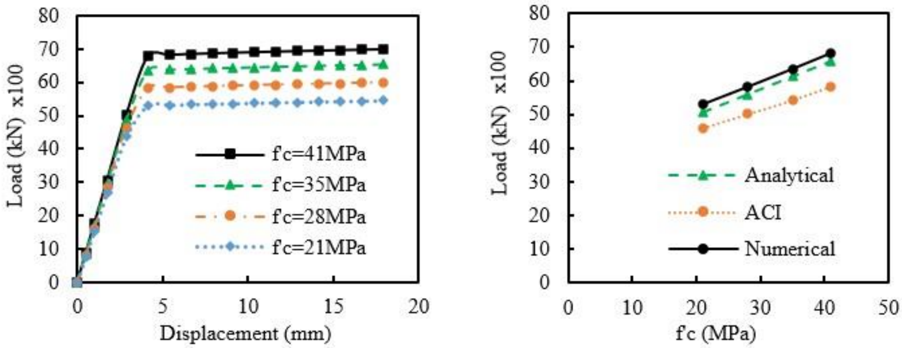


(a) (b)

Fig. 7. (a) Load capacity relation (b) Eigen Buckling analysis result

Table 5. Capacity of Specimens having different f'c

SP ID	B (mm)	t (mm)	L (mm)	B/t	L/B	fy (MPa)	f'c (MPa)	P_{Ana} (kN)	P_{Num} (kN)
G312C21	300	12	3000	25	10	250	21	5272	5292
G312C28	300	12	3000	25	10	250	28	5805	5810
G312C35	300	12	3000	25	10	250	35	6338	6345
G312C41	300	12	3000	25	10	250	41	6795	6814



(a) (b)

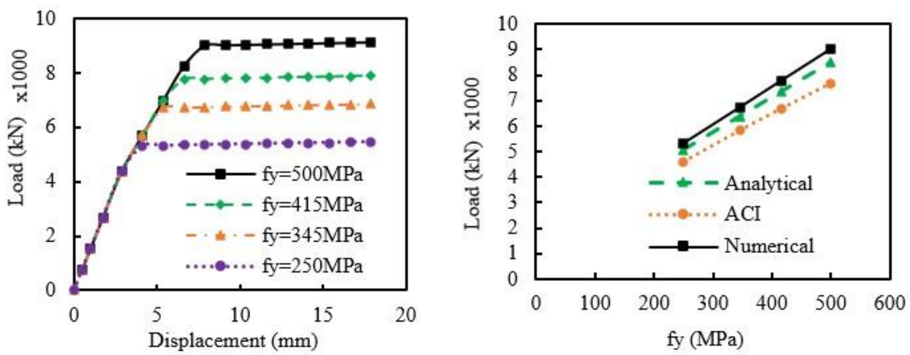
Fig. 8. (a) Load displacement curve (b) Capacity curve for different f′c

3.4 Effect of steel strength (f_y)

The strength of steel plates is a vital consideration in the design and evaluation of composite columns. The tensile strength of steel is a critical parameter in parametric studies and significantly contributes to the strength of composite columns. The strength of the steel plate in a composite column denotes its capacity to endure compressive loads that aim to diminish its dimensions. The strength of steel plates is a vital consideration in the design and evaluation of composite columns. The tensile strength of the steel in composite columns is essential for ascertaining the total load-bearing capacity and stability. Table 6 displays the findings of steel strength variation. Fig. 9(a) depicts the numerical load-displacement curve and Fig. 9(b) gives the capacity curve for various strengths of steel.

Table 6. Capacity of Specimens having different f_y

SP ID	B (mm)	t (mm)	L (mm)	B/t	L/B	fy (MPa)	f'c (MPa)	P_{Ana} (kN)	P_{Num} (kN)
G412S250	300	12	3000	25	10	250	21	5272	5302
G412S345	300	12	3000	25	10	345	21	6667	6708
G412S415	300	12	3000	25	10	415	21	7695	7752
G412S500	300	12	3000	25	10	500	21	8944	9013



(a) (b)

Fig. 9. (a) Load displacement curve (b) Capacity curve for different f_y

4 Conclusion

The axial capacity of concrete-filled fabricated steel box composite columns (CFFSBCs) was determined using various design code equations and numerically simulated failure load capacities. The study demonstrated that CFFSBCs exhibit enhanced axial strength with increased plate strength, indicating that higher plate strengths correspond to improved column capacity. The axial strength of these columns is influenced by the B/t ratio, L/B ratio, and the strengths of the steel and concrete. Key findings are summarized below:

1. The axial capacities calculated using different design codes exposed that the AISC code is the more conservative compared to the others;
2. Among the design codes, EC4 provided the highest axial capacity, with numerical results closely matching those of the EC4 code;
3. The ACI code incorporates a strength reduction factor, leading to lower calculated capacities compared to the ultimate values; however, it slightly overestimates capacity relative to the AISC code;
4. The axial strength of CFFSBC columns increased with the reduction in the B/t ratio, as thicker steel plates contributed to greater capacity;
5. A reduction in the L/B ratio led to an increase in the axial capacity of the columns;
6. The numerical simulations closely matched the analytical results, and the variations observed were within acceptable limits.

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