Industrial Engineering Journal
ISSN: 0970-2555
Volume : 51, Issue 03, March : 2022

Under Monotonic Axial Compression Load, Finite Element-Based Performance Study of Encased Composite Columns

*1 Dr. Sivasubramaniam, Mr Ranjan Kumar Sahoo
*1Asso. Professor, Dept. of Civil Enghineering,NIT, BBSR,
Asst. Professor, Dept. of Civil Engineering, NIT, BBSR
Email: sivasubramaniyam@thenalanda.com, ranjansahoo@thenalanda.com

ABSTRACT: The performance of fully encased composite columns under monotonic axial stress was examined using finite element simulation, and the findings are presented in this work. The impact of the concrete's compressive strength and the size of the reinforcement was the primary focus of the inquiry into the specimen's damage characteristics and performance. Concrete damage plasticity (CDP), which encompasses the hardening and softening behaviours, was used to simulate the concrete material, while metal plasticity was used to model the steelUsing the use of previously completed experimental work and manual calculations based on Eurocode 4, the findings of the current investigation were validated. The increase in concrete strength, according to the FEA results, greatly reduced damage to the concrete matrix. An increase in longitudinal reinforcement diameter reduces the equivalent plastic strain in both structural steel and reinforcement bars while maintaining other variables constant. The outcomes additionally demonstrated that the analytical solution was fairly validated by the numerical simulation.

1. Introduction

Composite construction is gaining popularity throughout the world due to its structural capabilities, particularly in high-rise structures and seismically active areas. The use of steel-concrete structures helps structural systems meet their performance and functional requirements better. Concrete-encased steel (CES) composite columns are becoming more and more common in top-down or basement construction due to their improved structural performance as compared to traditional rein-forced concrete (RC) columns [1-3]. Construction of composite structures has the benefit of the strength of the structure coming from the combined resistance of steel and concrete. Steel buildings often have higher strength-to-weight and stiffness-to-weight ratios, as well as increased ductility [4–7]. Costs for the early and ongoing phases of a project are decreased when composite construction is used properly [8, 9]. Labor costs and on-site temporary employment are the main causes of high costs in the construction sector. The price and duration of building a high-rise structure and a bridge, respectivelhe effectiveness of traditional reinforced concrete construction is greatly impacted by temporary activities. One of the crucial paths is passed during the construction of reinforced concrete columns. As a result, it is necessary to cut down on the price and duration of on-site temporary work in the construction business [10, 11]. The most popular kind of composite construction is one which consists of encased composite columns. Improved strength, stability, stiffness, fireproofing, and corrosion protection are all provided by fully encased composite columns (FECs) [12–15].

A steel-concrete composite column essentially consists of a tubular steel segment that is either concrete-filled or concrete-encased. In a composite-framed construction, load-bearing components are typically made of steel-concrete composites. By adding additional reinforcement, a composite column's overall resistance to external loading is improved. Under external pressure and fire conditions, this prevents excessive concrete spalling [16, 17]. To now, numerous research have been

conducted to study the performance of composite col- umns under diferent loading conditions, including combined action [1, 13, 18–24]. In addition, concrete- filled steel tubes under cyclic load were also reported in previous studies [24–26]. Previous studies showed that there are diferent factors that influence the performance of the composite column. For instance, an increase in the compressive strength of concrete yields an improved capacity for the composite column [4, 27–29]. The pro- vision of confinement has also an efect on the load- carrying capacity, which depends on the steel section shape and the spacing between the transverse re- inforcements [1, 30–32]. The efects of cross-section, column height, and confinement were also reported for diferent eccentricities and structural steel shapes [33–36]. Previous studies conducted on experimental and ana- lytical studies of square composite columns with two interlocking spirals revealed an improved axial com- pressive capacity and ductility behavior of composite columns. The utilization of a circular and star-shaped spiral enhances the confinement efect for the core con-crete [23, 24, 37–39]. According to Jin et al. [40], theconstraint efect under concrete is enhanced as the con-finement increases and the failure behavior of the column becomes less brittle. The cross-section of steel tubes and the addition of steel fiber also matter for the performance of a composite column. Zhang et al. [41] stated that the utilization of circular steel tubes is

Industrial Engineering Journal
ISSN: 0970-2555
Volume : 51, Issue 03, March : 2022

recommended over a square steel tube to meet the desired design strength requirement and provide better confinement to core concrete. Furthermore, Zhang et al. [41] quantified that the utilization of steel fibers efectively improved the ductility and reduced the crack width.

Finite element analysis (FEA) i UGC CARE Group-1,
494
s a widely utilized method to study the performance and failure characteristics of en- gineering structures. This computer-based analysis also helps to study the complex behavior that accounts for the material and geometric nonlinearity of steel-concrete composite columns. Earlier studies showed that FEA can fairly validate the results obtained from experimental tests [42–48]. The study result reported by Shih et al. [23] fora fully encased composite column (FEC) made of high- strength steel and concrete stated that finite element analysisreasonably validated the experimental result. Ellobody and Young [43] and Lai et al. [49] also quantified the nonlinear 3- D finite element model as an important tool to evaluate the performance of composite columns. Finite element analysisis applied to investigate the complex load transfer mecha- nism in composite structures such as a concrete-encased column [13, 18, 24, 50].

The focus of this study is to investigate the damage and performance characteristics of an encased composite col- umn under monotonic axial load. The strength of the concrete and the size of the reinforcing bars were used as the main parameters in this study. Nonlinear finite element analysis (FEA) was conducted for the damage behavior and load-carrying capacity of the composite column. Analytical design checks were carried out based on the simplifieddesign method of the Eurocode 4 (EC4) plastic design approach. The FEA and analytical result verifications were conducted by comparing the experimental test reported by Lai et al. [1].

2. Material Data and Test Specimens

Material Data. The material definition and an ap- propriate material model is a crucial element in finite element modeling. The material properties for concrete structural steel and reinforcing bars should be defined with appropriate material parameters. During the finite element analysis, the nonlinear material behavior of these materials was included in the numerical simulation. The comprehensive details of material models were described in the following sections.

Concrete Compressive Strength. Four classes of cy- lindrical compressive strength were utilized in this study, as shown in Table 1. The concrete specimen having a com- pressive strength of 52.3 MPa was adopted from an exper- imental test reported by [1]. The encased composite column specimen with this compressive strength was used as a control for the validation study under the current study. However, the remaining concrete compressive strength classes were utilized as additional study parameters for the performance investigation of the encased composite col- umns. The modulus of elasticity and Poisson’s ratio of these specimens were calculated based on Eurocode-2 provisions for the design of concrete structures [51].

Damage Plasticity Modeling. ABAQUS© softwareofers mainly the following three crack model options to simulate the damage behavior of concrete(1) smeared crackmodel, (2) brittle crack model, and (3) concrete damagedplasticity model. The concrete damaged plasticity model wasutilized in this study, incorporating the inelastic behavior ofconcrete under tension and compression, which in-corporates damage parameters [52]. Thus, in ABAQUS©software, the concrete material is usually simulated understatic and dynamic loading conditions using the concretedamaged plasticity model [53]. Tensile cracking and com-pressive crushing are the two main failure mechanismsconsidered for the damage plasticity model of concrete. Thetensile and compressive behavior of concrete under uniaxialload is described by the damaged plasticity model [54]. During modeling, the degradation of the elastic stifness intension and compression is considered for analysis. Fur-thermore, under cyclic loading, stifness recovery isaccounted for by this model. The response of concrete presented in Figure 1 was utilized in the current study [53].The tensile and compressive damage parameters, (d_c) and (d_t), are calculated by equations (1) and (2), respectively.

Table 1: Mechanical properties of concrete.

Concrete grade	Cylindrical compressive strength	Modulus	Poisson’s ratio	Remark

Industrial Engineering Journal
ISSN: 0970-2555
Volume : 51, Issue 03, March : 2022

	(MPa)	of elasticity (GPa)		
$C50$	52.3	32.9	0.2	*
$C25$	25	31	0.2	**
$C30$	30	33	0.2	**
$C35$	35	34	0.2	**

*Mechanical properties of concrete from experimental work [1]. **Mechanical properties of concrete based on Eurocode-2 provision [51].

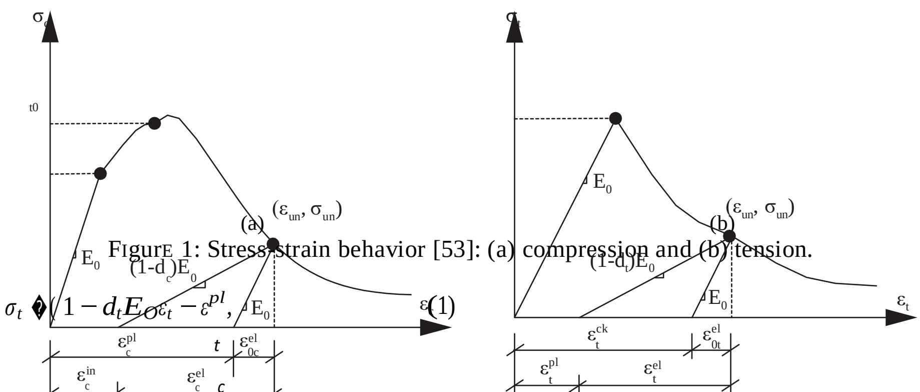


Figure 1: Stress-strain behavior [53]: (a) compression and (b) tension.

$$\sigma_t = (1-d_t E_O \varepsilon_t - \varepsilon^{pl}, \quad (1)$$

equal to 1.16. The dilation angle, which is the angle of in-clination of the failure surface towards the hydrostatic axis,

$$\sigma_c = (1-d_c E_O \varepsilon_c - \varepsilon^{pl}. \quad (2)$$

measured in the failure plane, was also considered [24, 53]. The dilation angle, ψ, is physically interpreted as a concrete

The strain hardening and softening behavior of the concrete were considered for the reinforced concrete during the analysis. To incorporate the complete tensile behavior of reinforced concrete, the input data for Young's modulus (E_0), stress (σ_t), cracking strain (ε_{tck}), and the damage parameter (d_t) were considered during the simulation. The cracking strain (ε_{tck}) was calculated from the total strain using the following equation:

$$\varepsilon^{ck} = \varepsilon - \varepsilon^{el}, \quad (3)$$

internal friction angle. Under this study, the dilation angles of ψ 32°, 34°, 36°, and ψ 38° were used for the corre- sponding concrete grades $C25$, $C30$, $C35$, and $C50$,respectively.

Steel Material Modeling. The steel materials were modeled as an elastoplastic material as given in Eurocode 3, 2005, Abaqus manual, and Eurocode 2, 2005 [51, 53, 56]. Figure 2 shows the true stress and logarithmic strain graph

that was utilized for the modeling of steel materials. To

where $\varepsilon_{ot}^{el} = \sigma_t/E_o$ is the elastic strain and ε_t is the total strain. Again, the plastic strains are determined from the following equations:

$$\varepsilon^{pl} = \varepsilon^{ck} - \frac{d_t}{(1-d_t)} * \frac{\sigma_t}{E_o}, \quad (4)$$

define the nonlinear behavior of the structural steel section and the reinforcement, the metal plasticity model was used. There true strain-stress behavior was used for steel material to account for the nonlinear behavior characteristics, which enable it to capture the postbehavior of the material [56]. The experimental stress and strain results of the uniaxial tension tests were converted to true stress and logarithmic plastic

Industrial Engineering Journal
ISSN: 0970-2555
Volume : 51, Issue 03, March : 2022

ε^{pl} � ε^{ck} – d_c

σ_c , ((5)

strain as inputs for the simulation using the following

c $1 - d_c$ E_0

where E_0 is the initial modulus of elasticity.

Parameters describing the state of the material in which the concrete undergoes failure under biaxial compression were also used in this study. The ABAQUS user's manual specifies that the default value for the ratio of the strength in the biaxial state to the strength in the uniaxial state (f_{b0}/f_{c0}) is

equations:

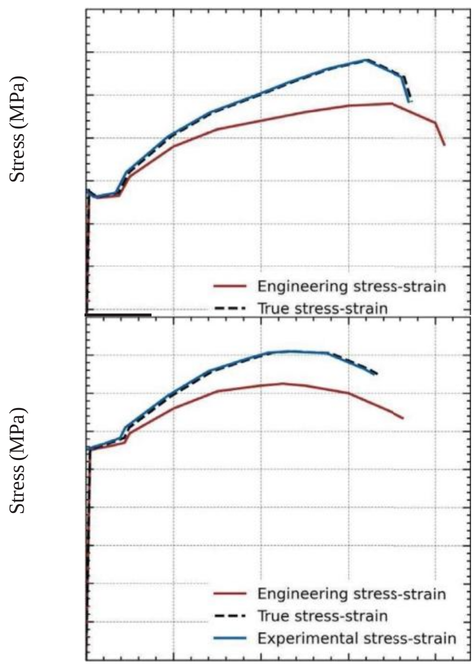
σ_{true} � $\sigma_{\text{nom}}(1 + \varepsilon_{\text{nom}},$ (6)

where ε_{nom} is the nominal or engineering strain and σ_{nom} isthe nominal or engineering stress

800
700
600
500
400
300
200
100

ε �ln (1 + ε , (7)true

nom



900
800
700
600
500
400
300
200
100

0.05

0.05

0.10
Strain

(a)

0.10
Strain
(c)

0.15

0.15

0.20
800
700
600
500
400
300
200
100
0
0.00

800
700
600
500
400
300
200
100
0
0.00
0.20

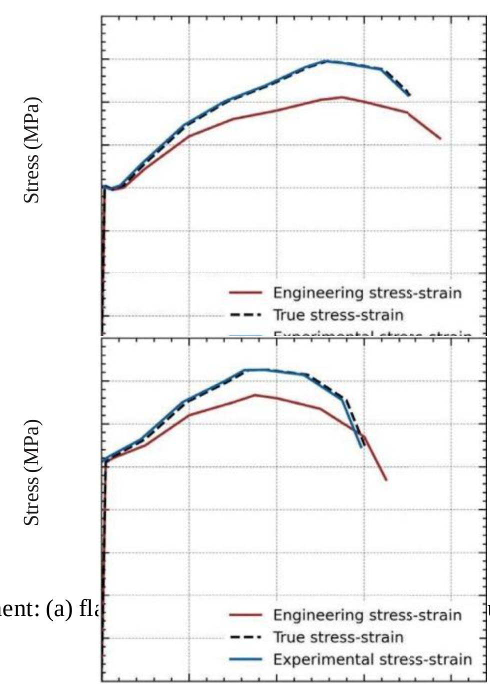


Figure 2: Stress-strain curves for structural steel and reinforcement: (a) fl udinal reinforcement;
(d) transverse reinforcement.

The steel material properties used for the finite elementsimulation are given in Table 2.

Test Specimens' Details. For the current study, an ex- perimentally tested specimen by Lai et al. [1] was utilized asa control for analytical and FEA validation. The behavior ofthe specimens during the loading was examined based on thefailure modes, peak load, and load-deflection plots. A col- umn section given in Figure 3 was utilized as a control in anexperimental test conducted by Lai et al. [1]. Analytical andfinite element analyses were carried out in this column to investigate the structural performance under compressive load. The variables utilized were the compressive strength ofthe concrete, the height of the column, and the longitudinal and transverse reinforcement size efects.

3. Numerical Simulation

General. Basically, the finite element analysis (FEA) requires defining geometry, material properties, assigning a mesh, analysis type, and boundary conditions for a given model. Finite element analysis (FEA) resulted in refined
results during the investigation of the flexural, fatigue, and axial performance of composite columns [20, 25, 42, 57]. The studies show that FEA is the best tool to understand the failure mechanism of a structural element under a given loading condition and even helps to predict the performance of structures under complex boundary, load, and geo- metrical conditions. Both material and geometric non- linearity were considered in the analysis. The load wasapplied using several load increments during the simulation.This helps the structure to remain in equilibrium by con- trolling nonlinear fluctuations in the structure's stifness at the end of each increment [24].

Finite Element Modeling of Encased Composite Column. The modeling procedures for each constituent part of an encased composite column were described one by one in this section. The encased composite column is composed of a structural steel section, longitudinal reinforcement, transverse reinforcement, and concrete. The concrete and structural steel are modeled using a three-dimensional 8- noded hexahedral (brick) element with educed integration (C3D8R). This helps the shear-locking efect during loading

Table 2: Steel material data [1].

Material		Yield stress (MPa)	Ultimate stress (MPa)	Density (kg/m^3)	Young's modulus (MPa)	Poisson's ratio
Steel sections	Flange	375	580	7,850	226,600	0.3
	Web	404	611	7,850	223,900	0.3
Reinforcement bars	Rebar	550	725	7,850	228,200	0.3
	Stirrup	510	667	7,850	197,700	0.3

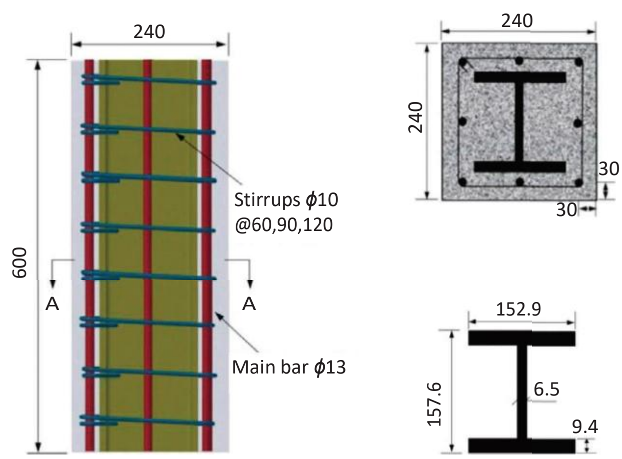


Figure 3: Dimension details of specimen [1].

[34]. For the reinforcement, the T3D2 element was used [53]. The assembled view of the column is depicted inFigure 4.

Loading and Boundary Conditions. The FEA model was created based on the experimental setup as shown in Fig- ure 5. The bottom end of the column was fixed, and the axialload was applied through a rigid body reference node at the center of the top loading plate. The rotations and horizontal translations at the top surface were fixed, and translation along the longitudinal downward direction was allowed. Thedisplacement control technique was used to apply the compressive crushing through the reference node at thecenter of the top loading plate. Figure 5 depicts the ex- perimental setup, boundary, and loading conditions of the current study.

Interactions Properties. Kinematic relationships were considered to ensure compatibility between interacting bodies. The first interaction type used was an embedded constraint.The embedded constraint was defined for the interaction be- tween concrete, structural steel, and reinforcement bar. The reinforcement bars and the structural steel were embedded under the concrete. Previous studies also stated that this optionensures a perfect bond between the concrete and embedded parts under the concrete [53, 58]. The concrete was defined asthe host region, and the steel sections were defined as the embedded elements. The interaction between the encased composite column and the support and loading plate is definedas a tie. Another interaction type used in this study is general surface-to-surface contact, which is used to define two con-tacting bodies in general [24].

Mesh. Finite element results are highly dependent on mesh types, control, and sizes. Studies showed that the provision of coarse mesh yielded brittle failures [59–62]. The mesh size is one of the factors contributing to the conver- gence criteria. It has been also reported that mesh fineness and coarseness have a significant efect on computation time[58, 63–66]. The guideline for maximum mesh size was already stated in the previous report [58, 67]. However, the fines of mesh are usually determined by the convergence ofresults and practical considerations. A mesh size of 20 mm was used in this study.

4. Result and Discussion

Manual Verification According to Eurocode 4. Before conducting the finite element analysis, the result from ex- perimental work was verified by using manual calculation according to Eurocode 4 [30] for the composite column. Thus, the steps to design encased steel columns subjected toaxial load are given as follows:

(1) Calculate the ultimate axial load, N_{Ed}
(2) Select a trial section and calculate geometricalproperties
(3) Determine the buckling length of the column, L_e
(4) Determine efective flexural stifness, EI_{eff}
(5) Determine plastic resistance, $N_{pl,Rk}$

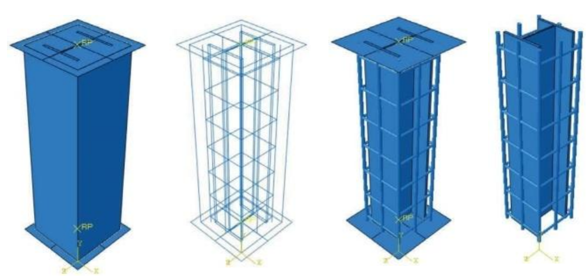
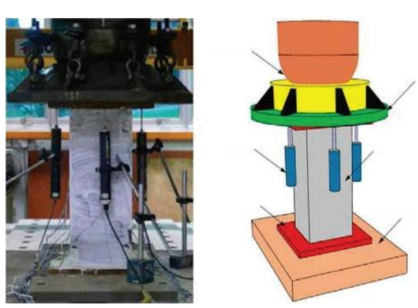


Figure 4: Assembled FEA model of encased composite column components.



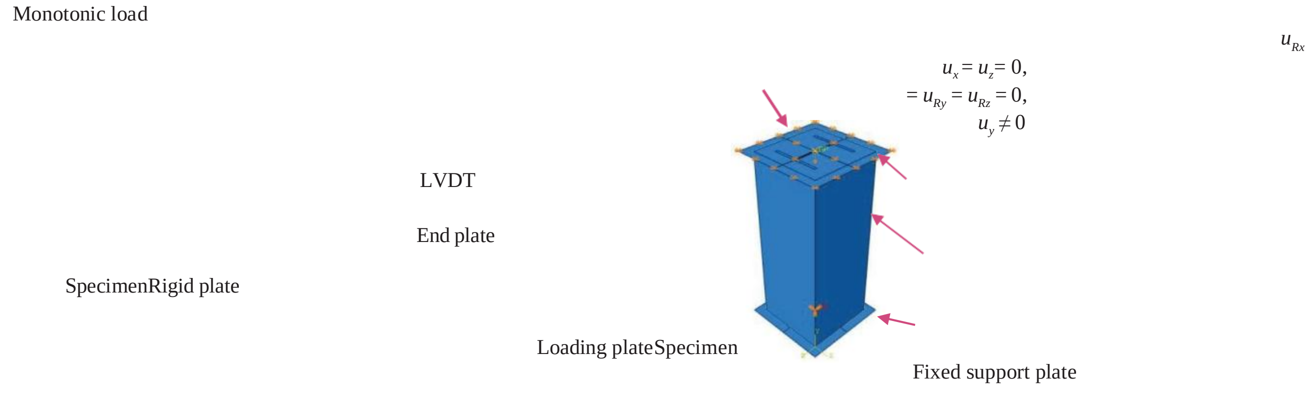


Figure 5: Experimental setup and boundary condition: (a) experimental test setup and instrumentations [1]; (b) FEA boundary conditions.

(6) Determine the relative slenderness of the section (λ) and

(7) Choose the buckling curve and compute the reduction factor, χ

(8) Determine buckling resistance, $N_{b,Rd}$

Radius of Gyration, i_y � 67.60mm i_z � 38.30mm

Moment of inertia, I_y � 1748cm^4 and I_z � 560cm^4, Efective length of the column � Le � 0.7 ∗ L � 0.7 ∗ 600 � 420 mm.

(9) Check if $N_{Ed} < N_{b,Rd}$, else return to step 2

Given Data

N_{Ed} � 4475.4kN

Steel section UC152 × 152 × 30.

Column cross-section, A_c � 240 × 240(mm^2) Characteristic cylindrical compressive strength ofconcrete, f_{ck} � 50MPa

Longitudinal reinforcement, 8∅13

Steel material properties are given in Table 2Column height, l � 600mm

Design Checks

(a) Geometrical properties of universal column (UC)section

Area of UC section, A_g � 3830mm^2

(b) Buckling length of the column (considering thebottom end is fixed and the top end is pinned)

L_e � 0.7 ∗ l � 0.7 ∗ 600mm � 420mm

(c) Efective flexural stifness, EI_{eff}, of the compositesection

EI_{eff} � $E_a I_a$ + $E_s I_s$ + $0.6 E_{cm} I_c$

where E_a � elastic modulus of structural steel 226, 600MPa (from Table 2); E_s � elastic modu lusof reinforcement � 228, 200MPa (from Table 2); E_{cm} � modulus of elasticity of concrete � $22(f_{cm}/10)^{0.3}$ GPa � $22 * ((50 + 8)/10)^{0.3}$ � 37, 278 MPa (Eurocode 2 [51]); I_a � moment of inertia of structural steel; I_c � moment of inertia of uncracked concrete section � $(b * h^3/12)$ � $[(240 * 240^2)/12]$ � 2, 764.8 ∗ 10^{5}mm^4; I_s � moment of inertia of the 8∅13 reinforcement bars � 8 ∗ π ∗ $D^4/64$ � 11, 215.88mm^4

Thus,

Industrial Engineering Journal
ISSN: 0970-2555
Volume : 51, Issue 03, March : 2022

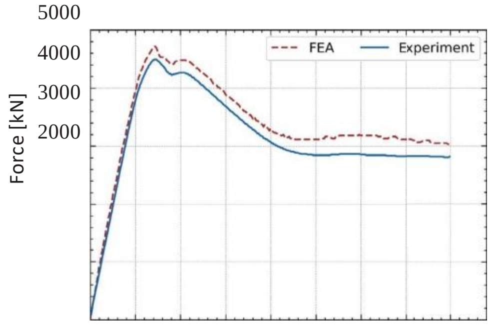


FIGURE 6: Comparative study between FEA and experimental test.

The deviation between the manual calculation andthe experimental test becomes

4.3. Efects of Concrete Strength. Obviously, it is a known fact that an increase in compressive strength yields enhanced load-carrying capacity of concrete structures; however, it is

$$\frac{4647.00 - 4475.40}{4647.00} * 100\% \approx 3.7\%. \quad (13)$$

difficult to predict how much damage to the concrete matrixis minimized by improving the compressive strength of concrete. Thus, finite element analysis shows very precise

For this calculation, it can be seen that the experimental test fairly validates the analytical solution.

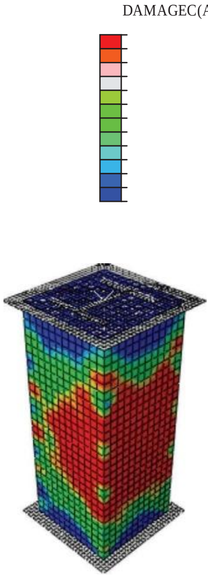
Finite Element Analysis Validation Study. To validate finite element analysis, an experimental work reported by Lai et al. [1] was used as a benchmark experiment. The encased composite column has a cross-section of 240×240 mm dimension with 600 mm height. A total of 8∅13 longitudinal reinforcement bars were provided, givinga reinforcement ratio of 1.84%. The transverse bars of ∅13 with a clear spacing of 120 mm, giving the volumetric ratioof 1.29% were used. The UC152 152 30 British steelsection was adopted, which accounts for 6.56% of the entiresection. This structural steel section is classified as class 1 according to EN1993-1-1, 2005 [56]. The characteristic cylindrical compressive strength of concrete is 50 MPa. The relevant material properties for the finite element analysis are presented in Section 2 under Tables 1 and 2. Further- more, the finite element analysis instrumentation and modeling parameters are also depicted in Section 3.

In this study, a mesh size of 20 mm fairly validates the experimental work. Results showed that the finite element analysis resulted in a close prediction of the experimental test with an accuracy of 95.20% for the ultimate load-carrying capacity of the encased composite column. The ultimate load obtained from finite element analysis (FEA) and experimental test were 4475.4 kN and 4701.01 kN, re-spectively. The deviation between the FEA and the experi- mental test is about 4.80%, which is within an acceptable range. Moreover, the comparative study shown in Figure 6 shows that the simulation fairly traces the postfailure be- havior of the encased composite column from the experi- mental test. Therefore, it has been observed that this validation result becomes a good starting point for the discussed parametric studies in the next sections.

Industrial Engineering Journal
ISSN: 0970-2555
Volume : 51, Issue 03, March : 2022

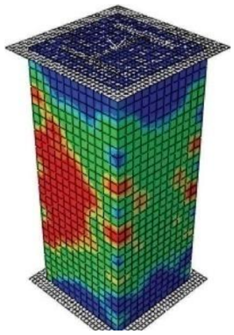
information about how much of the concrete matrix is damaged at a given ultimate load. The geometrical andmaterial properties used for the structural steel and re- inforcement bar are identical to those given in Section 4.2. Figure 7 clearly shows the efect of concrete strength on the damage characteristics of an encased composite column. The damage to the concrete is significantly minimized due to theincreased strength of the concrete. The load-carrying ca- pacity of the encased composite column increased with the increase in concrete compressive strengths, as shown in Figure 8. The load-carrying capacity of the column improved by about 6.38% and 5.93% for the concrete grades of f_{ck} 25 to f_{ck} 30 and f_{ck} 30 to f_{ck} 35, respectively. The capacity of the column improved by 11.93% on average as the compressive strength of concrete increased from f_{ck} 25 to f_{ck} 35, as depicted in Figure 8(b). From this study, we can understand that the damage to the concrete matrixcan be minimized by increasing the compressive strength of the concrete. Furthermore, an increase in concrete strength improves the load-bearing capacity of an encased composite column, as expected.

4.4. Efects of Reinforcement Ratio. The efect of longitudinalreinforcement is better understood by observing equivalent plastic strain (PEEQ), as shown in Figures 9(a)–9(c). Keeping other parameters constant, an increase in the re- inforcement ratio minimizes the equivalent plastic strain both in structural steel and reinforcement bars. The ultimate load of the encased composite column increased with the increase in reinforcement ratio, as shown in Figure 10. The finite element analysis also verified that the plastic resistance to compression of the composite section is directly pro- portional to the area of the reinforcing bar, as discussed in Section 4.1. The load-carrying capacity of the column im- proved by about 4.14% and 4.77%, for an increase in



(a)

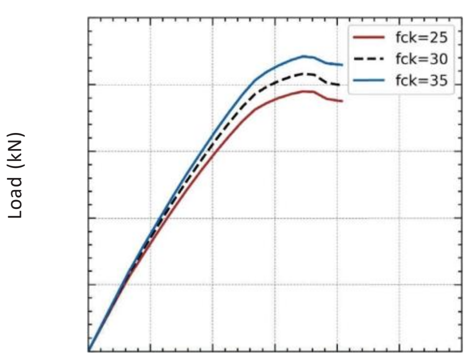
Industrial Engineering Journal
ISSN: 0970-2555
Volume : 51, Issue 03, March : 2022



(b)

DAMAGEC(Avg: 75%)
+7.149e-02
+6.553e-02
+5.958e-02
+5.362e-02
+4.766e-02
+4.170e-02
+3.575e-02
+2.979e-02
+2.383e-02
+1.787e-02
+1.192e-02
+5.958e-03
+0.000e+00

(FIgurE 7: Efects of concrete strength on damage characteristics of the encased composite column: (a)f_{ck} � 25; (b)f_{ck} � 30; (c)f_{ck} � 35.



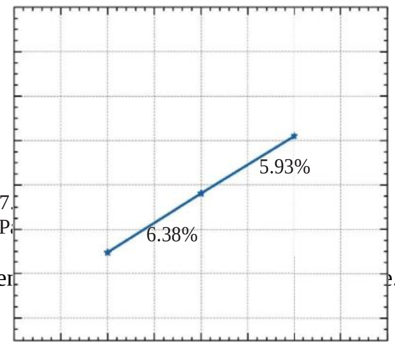
5000
4000
3000
2000
1000
0
0

Industrial Engineering Journal
ISSN: 0970-2555
Volume : 51, Issue 03, March : 2022

1 2 3 4 5 6
Displacement (mm)

(a)

5000
4800
4600
4400
4200
4000
3800
3600



Ultimate load (kN)

20.0 22.5 25.0 27.5 30.0 32.5 35.0 37.

Concrete compressive strength (MP

(b)

Figure 8: Comparative study: (a) load versus displacemen e.

PEEQ (Avg: 75%)

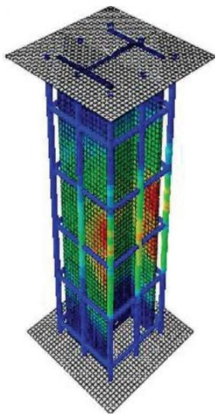
+2.704e-03
+2.479e-03
+2.254e-03
+2.028e-03
+1.803e-03
+1.578e-03
+1.352e-03
+1.127e-03
+9.015e-04
+6.761e-04
+4.507e-04
+2.254e-04
+0.000e+00

(a)

PEEQ (Avg: 75%)
+2.591e-03
+2.375e-03
+2.159e-03
+1.943e-03
+1.727e-03
+1.511e-03
+1.296e-03
+1.080e-03
+8.637e-04

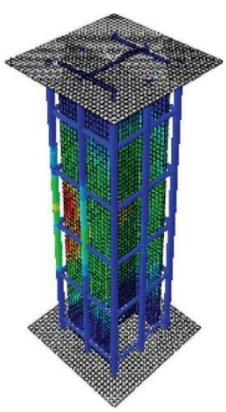
Industrial Engineering Journal
ISSN: 0970-2555
Volume : 51, Issue 03, March : 2022

+6.478e-04
+4.319e-04
+2.159e-04
+0.000e+00



(b)

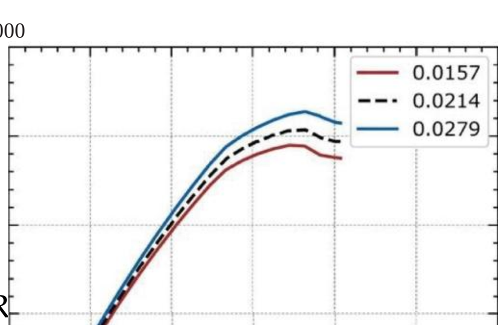
PEEQ (Avg: 75%)
+2.453e-03
+2.249e-03
+2.044e-03
+1.840e-03
+1.635e-03
+1.431e-03
+1.227e-03
+1.022e-03
+8.177e-04
+6.133e-04
+4.089e-04
+2.044e-04
+0.000e+00

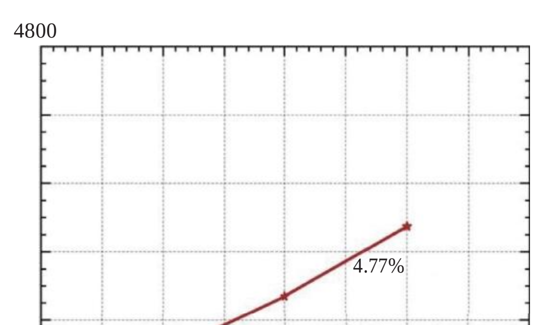


(c)

FIGURE 9: Efects of reinforcement ratio on damage characteristics of the encased composite column: (a)0.0157; (b) 0.0214; (c) 0.0279.

reinforcement ratio from 0.0157 to 0.0214 and 0.0214 to 0.0279, respectively. The capacity of the column improved by 8.91% on average when the reinforcement ratio increased from 0.0157 to 0.0279 while keeping the number of bars and other parameters constant, as depicted in Figure 9(b). Thus, from this study, we can understand that an increase in reinforcemet ratio minimizes the plastic strain under structural steel and reinforcing bars in fully encased steel





4000

3000

Load (kN)

2000

1000

0 0 1 2

3 4 5 6
4600

4400

4200

4000

3800

3600

Ultimate load (kN)

10

11 12 13

17 18

Displacement (mm)

(a)

Reinforcement diameter (mm)

(b)

FIGURE 10: Comparative study for reinforcement efect(a) load versus displacement study; (b) comparison in percentage.

composite columns. A recent study also depicted that an increase in the reinforcement ratio tends to increase the ultimate load-carrying capacity [68].

5. Conclusions

In this study, nonlinear 3D finite element modeling of square-encased composite columns under monotonic axial compression load was performed. The concrete material was modeled using concrete damage plasticity (CDP), which incorporates the hardening and softening behaviors, and the steel was modeled using metal plas- ticity. The efects of concrete strength and reinforcement ratio were investigated to understand the capacity and stress-strain distribution under the composite column. The analysis result from the current study fairly validates the experimental result by capturing the postsoftening part of the test specimen. Furthermore, the result from experimental work was verified prior to FEA by using manual calculation according to Eurocode 4 and a sim- plified method to design encased steel columns under axial compression. Based on the analysis and discussion presented in this study, the following conclusions were drawn:

(i) A comparative study was conducted for finite ele- ment analysis to estimate the ultimate load-carrying capacity between analytical calculation according toEurocode 4 and experiment test. It has been ob- served that the finite element analysis resulted in a close prediction of the experimental test with an accuracy of 95.20% for the ultimate load-carrying capacity of the encased composite column.

(ii) It has been observed that an appropriate material definition and mesh size selection during finite element analysis (FEA) helps to obtain refined postsoftening failure behavior of the composite volume form load versus displacement plot.

(iii) The increase in the compressive strength of concrete yields a reduction in the damage to the concrete matrix and improves the load-carrying capacity of the com-posite column. It has been observed that the capacity ofthe column improved by 11.93% on average as the compressive strength of concrete increased from f_{ck} ⧫ 25 to f_{ck} ⧫ 35 by keeping other parameters constant.

(iv) An increase in reinforcement ratio minimizes the equivalent plastic strain both in structural steel and reinforcement bar, and it has been observed that theplastic resistance to compression of the composite section is directly proportional to the area of the reinforcing bar. The capacity of the column improved by 8.91% on average when the diameter of the bar increased from 0.0157 to 0.0279 while keeping the number of bars and other parameters constant.

(v) In general, nonlinear 3D finite element modeling isthe finest tool to investigate the performance and damage behavior of composite structures by in-corporating correct material modeling.

Data Availability

The data used to support the findings of this study arepresented in the manuscript.

References

[1] B. Lai, J. R. Liew, and M. Xiong, "Experimental study on high strength concrete encased steel composite short columns," *Construction and Building Materials*, vol. 228, Article ID 116640, 2019.

[2] B. Lai and J R. Liew, "Axial-moment interaction of high strength concrete encased steel composite columnsexperimental investigation," *Journal of Construc- tional Steel Research*, vol. 175, Article ID 106370, 2020.

[3] B. Lai, J. R. Liew, and A. L. Hoang, "Behavior of high strength concrete encased steel composite stub columns with C130 concrete and S690 steel," *Engineering Structures*, vol. 200, Article ID 109743, 2019.

[4] B. Lai, J. Richard Liew, and T. Wang, "Buckling behaviour of high strength concrete encased steel composite columns," *Journal of Constructional Steel Research*, vol. 154, pp. 27–42, 2019.

[5] P. Collin, M. Nilsson, and J. Häggström, *International workshop on Eurocode 4-2, Composite Bridges*, Lulea Uni- versity of Technology, Lulea, Sweden, 2011.

[6] V. M. Karbhari and L. Zhao, "Use of composites for 21st century civil infrastructure," *Computer Methods in Applied Mechanics and Engineering*, vol. 185, no. 2-4, pp. 433–454, 2000.

[7] M. Kazem Sharbatdar, A. Kheyroddin, and E. Emami, "Cyclic performance of retrofitted reinforced concrete beam-column joints using steel prop," *Construction and Building Materials*, vol. 36, pp. 287–294, 2012.

[8] D. K. Kim, *A Database For Composite Columns*, Georgia Institute of Technology, Atlanta, GA, USA, 2005.

[9] Y. S. Song, J. R. Youn, and T. G. Gutowski, "Life cycle energy analysis of fiber-reinforced composites," *Composites PartAApplied Science and Manufacturing*, vol. 40, no. 8,pp. 1257–1265, 2009.

[10] J. Y. Oh, D. H. Lee, J. Lee, K. S. Kim, and S. B. Kim, "Ex- perimental study on reinforced concrete column incased in prefabricated permanent thin-walled steel form," *Advances inMaterials Science and Engineering*, vol. 2016, Article ID 3806549, 11 pages, 2016.

[11] P. Hopkinson, H. M. Chen, K. Zhou, Y. Wang, and D. Lam, "Recovery and reuse of structural products from end-of-life buildings," *Proceedings of the Institution of Civil Engineers -Engineering Sustainability*, vol. 172, no. 3, pp. 119–128, 2019.

[12] S. Rahman, M. Begum, and R. Ahsan, "Comparison between experimental and numerical studies of fully encased com- posite columns," *International Journal of Structural and Construction Engineering*, vol. 10, pp. 762–769, 2016.

[13] M. S. Rahman, *Behaviour and Strength of Fully Encased Composite Columns*, pp. 1–198, Bangladesh University Of Engineering And Technology, Dhaka, Bangladesh, 2016.

[14] S. A. Mirza and E. A. Lacroix, "Comparative strength analyses of concrete-encased steel composite columns," *Journal ofStructural Engineering*, vol. 130, pp. 1941–1953, 2004.

[15] S. Priya, R. Karthick, and V. Chandrikka, "Review on steel concrete composite column," *International Research Journal of Engineering and Technology*, vol. 6, pp. 450–454, 2019.

[16] J. F. Hajjar, "Composite steel and concrete structural systems for seismic engineering," *Journal of Constructional Steel Re- search*, vol. 58, no. 5-8, pp. 703–723, 2002.

[17] S. Rahman, M. Begum, and R. Ahsan, "Comparison between experimental and numerical studies of fully encased com- posite columns," *International Journal of Structural and Construction Engineering*, vol. 10, pp. 756–763, 2016.

[18] Y. F. An, L. H. Han, and C. Roeder, “Flexural performance of concrete-encased concrete-filled steel tubes,” *Magazine of Concrete Research*, vol. 66, no. 5, pp. 249–267, 2014.
[19] E. Ellobody and B. Young, “Investigation of concrete encasedsteel composite columns at elevated temperatures,” *Thin-Walled Structures*, vol. 48, no. 8, pp. 597–608, 2010.
[20] E. Ellobody, B. Young, and D. Lam, “Eccentrically loaded concrete encased steel composite columns,” *Thin-Walled Structures*, vol. 49, no. 1, pp. 53–65, 2011.
[21] C. Dundar, S. Tokgoz, A. K. Tanrikulu, and T. Baran, “Be- haviour of reinforced and concrete-encased composite col- umns subjected to biaxial bending and axial load,” *Building and Environment*, vol. 43, no. 6, pp. 1109–1120, 2008.
[22] C. S. Kim, H. G. Park, K. S. Chung, and I. R. Choi, “Eccentric axial load testing for concrete-encased steel columns using 800 MPa steel and 100 MPa concrete,” *Journal of Structural Engineering*, vol. 138, no. 8, pp. 1019–1031, 2012.
[23] T. H. Shih, C. C. Chen, C. C. Weng, S. Y. L. Yin, and J. C. Wang, “Axial strength and ductility of square composite columns with two interlocking spirals,” *Journal of Con- structional Steel Research*, vol. 90, pp. 184–192, 2013.
[24] K. Z. Mulgeta Mersha and E. C. Agon, *Investigation on Efect of Diferent Steel Section on the Performance of Encased Composite Column*, Jimma Institute of Technology, Jimma University, Jimma, Ethiopia, 2020.
[25] L. H. Han, F. Y. Liao, Z. Tao, and Z. Hong, “Performance ofconcrete filled steel tube reinforced concrete columns sub- jected to cyclic bending,” *Journal of Constructional Steel Research*, vol. 65, no. 8-9, pp. 1607–1616, 2009.
[26] W. W. Qian, W. Li, L. H. Han, and X. L. Zhao, “Analytical behavior of concrete-encased CFST columns under cycliclateral loading,” *Journal of Constructional Steel Research*, vol. 120, pp. 206–220, 2016.
[27] W. L. A. de Oliveira, S. De Nardin, A. L. H. de Cresce El Debs et al., “Influence of concrete strength and length/diameter on the axial capacity of CFT columns,” *Journal of Constructional Steel Research*, vol. 65, no. 12, pp. 2103–2110, 2009.
[28] S. A. Mirza, “Parametric study of composite column strengthvariability,” *Journal of Constructional Steel Research*, vol. 14, no. 2, pp. 121–137, 1989.
[29] Y. Li, X. Wu, X. Lis, K. Zhang, and C. Gao, “Compression performance and calculation method of thin-walled pre- fabricated steel tube lightweight concrete columns,” *Advances in Civil Engineering*, vol. 2022, p. 11, 2022.
[30] Eurocode 4:, “Standard Design of Composite Steel and Concrete Structures - Part 1-1 General Rules and Rules for Buildings,” *European Committee for Standardization*, Brus- sels, Belgium, 2004.
[31] D. H. Nguyen and W. K. Hong, “Part I failure criteria of the steel-concrete columns (SRC columns) confined by cross- shaped flange sections,” *Journal of Asian Architecture and Building Engineering*, vol. 20, no. 2, pp. 179–192, 2021.
[32] M. H. Lai and J. C. M. Ho, “Confinement efect of ring-confined concrete-filled-steel-tube columns under uni-axial load,” *Engineering Structures*, vol. 67, pp. 123–141, 2014.
[33] M. Begum, R. G. Driver, and A. E. Elwi, *Numerical Simu- lations of the Behaviour of Partially Encased Composite Col- umns*, Heritage, Canada, 2007.
[34] M. K. I. Khan, C. K. Lee, and Y. X. Zhang, “Parametric study on high strength ECC-CES composite columns under axial compression,” *Journal of Building Engineering*, vol. 44, Article ID 102883, 2021.
[35] B. Lai, J. R. Liew, A. Venkateshwaran, S. Li, and M. Xiong, “Assessment of high-strength concrete encased steel com- posite columns subject to axial compression,” *Journal of Constructional Steel Research*, vol. 164, Article ID 105765, 2020.
[36] C. Kim, H. Park, M. Asce, K. Chung, and I. R. Choi, “Eccentric axial load capacity of high-strength steel-concrete composite columns of various sectional shapes,” *Journal of Structural Engineering*, vol. 140, no. 4, 2014.
[37]