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Effect of load eccentricity on buckling behavior of FRP composite columns with open and closed cross sections

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Abstract. Fiber reinforced polymer (FRP) columns are increasingly being used in various engineering fields due to its high strength to weight ratio and corrosion resistance. Being a thin-walled structure, their designs are often governed by buckling. Buckling strength depends on state of stress of elements which is greatly influence by stacking sequence and various inaccuracies such as geometric imperfections and imperfections due to eccentricity of compressive load and non-uniform boundary conditions. In the present work, influence of load eccentricity on buckling strength of FRP column has been investigated by conducting parametric study. Numerical analyses were carried out by using finite element software ABAQUS. The finite element (FE) model was validated using experimental results from the literature, which demonstrated good agreement in terms of failure loads and deformed shapes. The influence of load eccentricity on buckling behavior is discussed with the help of developed graphs.

Keywords: buckling; eccentric load; finite element analysis; FRP laminate; stability

1. Introduction

Due to its various mechanical and physical characteristics, including their high stiffness and strength, low weight and resistance to corrosion, FRP composites are increasingly being used in many engineering fields such as civil, aerial, and marine. Automotive and aerospace sectors were the first industries to adopt FRP composites. In later years, civil engineering-related applications increased. They are employed as structural elements in buildings and bridges as beams and columns in civil engineering. Especially, both lightweight and high strength make GFRP profiles particularly attractive for the construction industry as members of truss, tower, elements of built-up columns and bracing members (Boscato *et al*. 2013). However, buckling has a significant impact on their load carrying capacity because of their thin-walled structure (Aktas and Balcioglue 2014, Topal 2017, Kasiviswanathan and Upadhyay 2021a, b, Kasiviswanathan and Anbarasu 2021).

FRP columns under compressive stress can buckle locally or globally which reduces the stiffness properties. Previous researchers have attempted to study the global and local behavior of column and proposed equation to predicts the capacity, but they constrained their studies with axial

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load. For example: Test findings for axially loaded FRP high slender I and box type profiles have been presented by Zureick and Scott (1997). Based on analytical, numerical and experimental results, Barbero (1998, 2000) and Hashem and Yuan (2001) showed that the Euler theory could be used to estimate the global buckling strength with a good level of accuracy. Kollar (2003) investigated axially loaded compression members and created formulae to compute local buckling strength of structural elements such as columns and beams. For FRP wide-flange columns, Qiao and Zou (2003) developed an explicit equation to determine the local compressive buckling strength. Puente *et al*. (2006) performed testing on PFRP hollow circular columns to estimate the strength of the sections. A unified design expression has been proposed by Vanevenhoven *et al*. (2010) to determine the critical load of pultruded fiber reinforced columns subjected to global and local buckling. Cardoso *et al*. (2014) created the compressive load prediction equation for pultruded glass fiber reinforced polymer (GFRP) square columns.

Generally, FRP columns are designed under ideal compression conditions. One of the key presumptions is that axial loads will be applied to the column. The column will be subjected to both bending and compression when the load acts eccentrically. The impact of eccentricity of load on buckling strength has been investigated by Wysmulski and Debski (2017), and Desbski *et al*. (2020). Their findings demonstrate that eccentric load significantly influences columns buckling strength under compression. However, they constrained their studies with particular laminate and sections.

The buckling strength of a column is affected by state of stress, which is impacted by the laminate configuration and geometric imperfections. The sensitivity of geometric imperfections on thin-walled structures has been studied by using experimental and numerical methods by various researchers. Zhan and Wu (2018, 2019) discovered a significant variance between known equations and the Euler formula. Therefore, Zhan and Wu (2018, 2019) introduced a novel closed-form design equation to calculate critical strength of globally loaded pultruded doubly symmetric cross-sections. The buckling behaviour of pultruded fiber reinforced polymer (PFRP) I section profile subjected to axial compression was examined by Kulkarni *et al*. (2020). They discovered a significant distinction between numerical analysis and experimental investigation. It can be due to an assumed artificial defect. According to conclusions drawn from earlier literature, geometric nonlinearity and geometric defects have significant impact on strength of GFRP columns. Li and Qiao (2015) and Ascione (2014) have studied laminated beams and columns and reported that geometric imperfection has significant impact of stability. Kasiviswanathan and Anbarasu (2022) have studied the axially loaded FRP box columns by considering geometric imperfections. The impact of boundary conditions on axially loaded channel columns has been studied by Urbaniak *et al*. (2015).

Given the aforementioned information, it is important to identify the critical load before a structure starts to lose stability. It turns out that methods for evaluating critical loads on real structures are poorly understood, which makes the design of such systems more challenging (Tsai and Wu 1971, Tsai and Hahn 1980, Caelsson *et al*. 2014). An alternative technique for determining critical loads is finite element numerical analysis (FE). Because FE analysis has no restrictions on boundary and loading conditions, it is being used in a various of engineering disciplines. To determine the critical loads, many researchers have employed FE analysis (Zienkiewicz and Taylor 2000, Arani *et al*. 2011, Kolakoeski and Mania 2013, Nunes *et al*. 2013, and Debski *et al*. 2018).

From the literature, it can be noticed that numerous studies explore the buckling behaviour of FRP columns under ideal conditions, but very few take load eccentricity and different inaccuracies into consideration. In this study, the buckling behaviour of FRP columns has been examined by

Table 1 Variables of shear strength database

E_L (GPa)	E_T (GPa)	G_{LT} (GPa)	υ_{LT}	υ_{TL}
143.52	5.83	3.84	0.36	0.0146

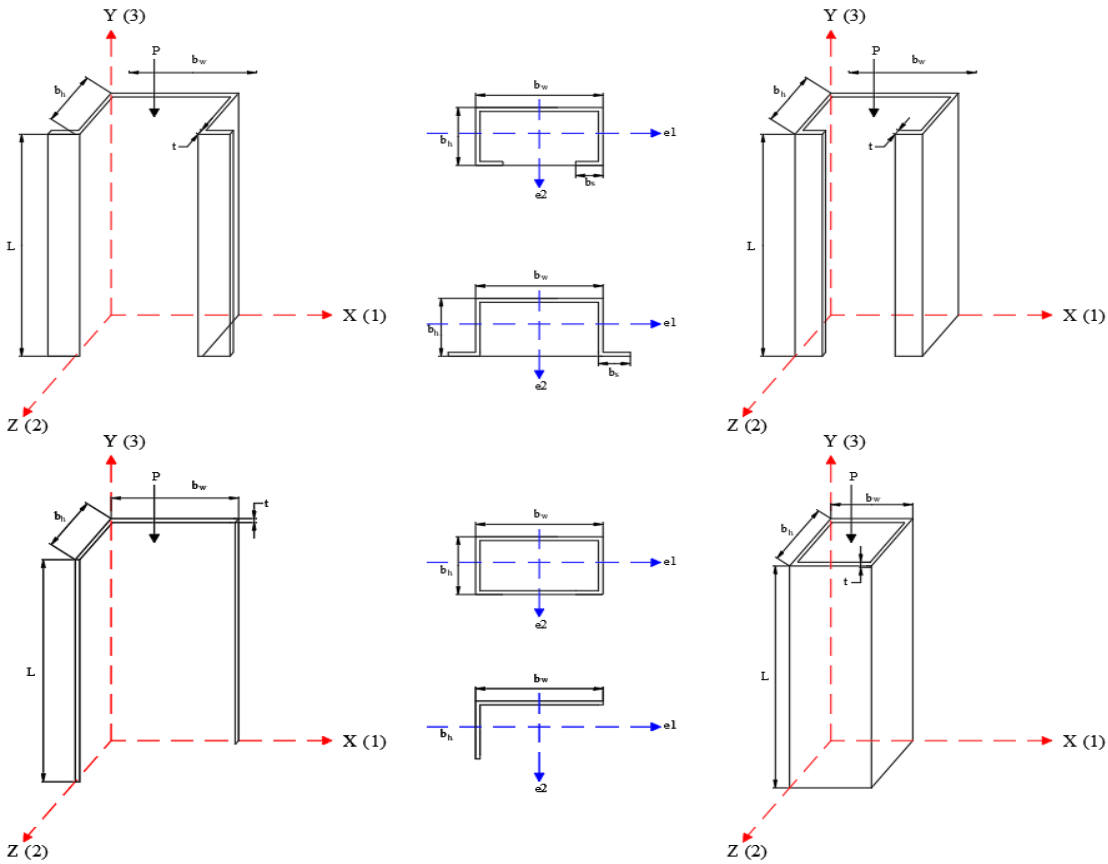


Fig. 1 Cross-section notations of PFRP column profiles

taking accidental eccentricity in both the major and minor axes into account. The effect of load eccentricity on the buckling behaviour of a FRP column is discussed using graphics.

2. Database

2.1 General

The finite element analysis (FEA) software ABAQUS (2011) was used to construct the numerical models. The accuracy of the FE models was confirmed by comparing results from the literature. The database was developed through the use of parametric analysis to assess the influence of load eccentricity on the buckling strength of a FRP column.

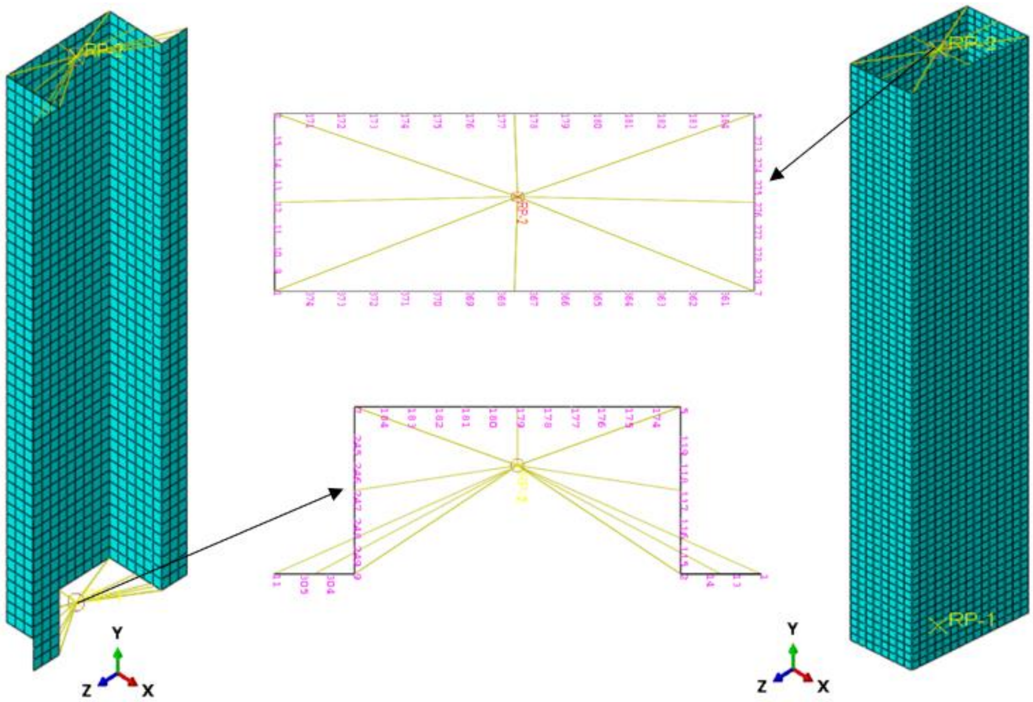


Fig. 2 Discrete model of column with open and closed cross-section

2.2 Material and geometry properties

Carbon fiber reinforced polymer (CFRP) mechanical properties from Debski *et al*. (2020) are used to model the angle column components. Table 1 lists the mechanical properties that were used in this study. Figure 1 shows the geometry details of FRP columns.

2.3 Element type and mesh convergence study

FE column models are discretized using the widely used element S4R, as shown in Fig. 2. Other studies have employed this element successfully in numerical modelling (Debski *et al*. (2020) and Kasiviswanathan and Anbarasu (2021)). This element has four nodes, each of which has six degrees of freedom: translation in the X, Y, and Z directions, as well as rotation around the X, Y, and Z axes.

When performing FE analysis, coarser elements produce results faster, but with lower accuracy. On the other hand, smaller elements, produce more accurate results but take longer to compute. To address the computational source as well as accuracy, a mesh convergence study was conducted. Successive runs, each with decreasing size of the element, were performed. Fig. 3 summarizes the results of the convergence analyses for C1 section based on changing element sizes. It can be seen that as the mesh size decreases from 15 (mm) and mesh is getting dense, it converges for 5 and 2.5 (mm) mesh sizes. The minimum element size of 5 mm was then employed in subsequent analyses. Similar type of study was performed for other section, all section buckling load (minimum) is converged at 5mm mesh size.

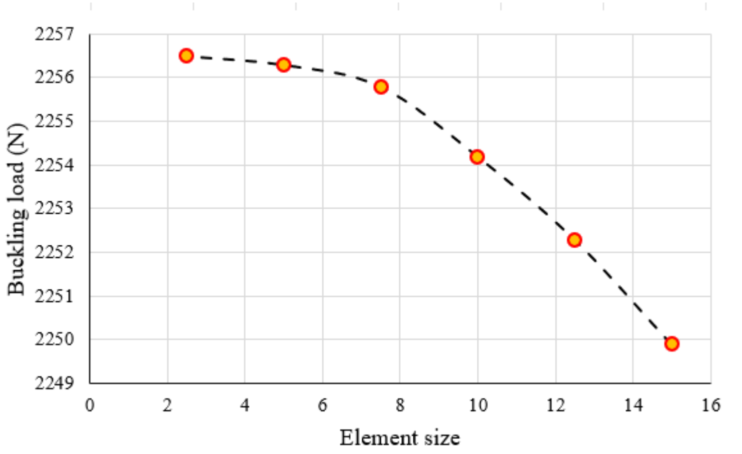


Fig. 3 Mesh convergence analysis

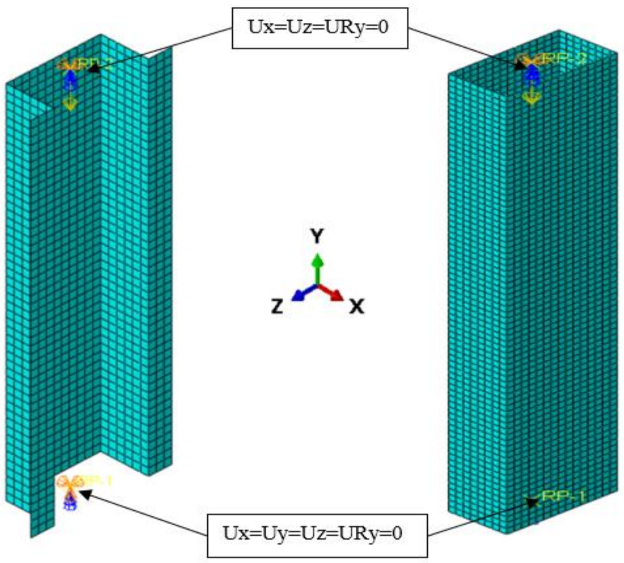


Fig. 4 Applied boundary conditions with open and closed cross-section

2.4 Loading and boundary conditions

In a parametric study, to determine buckling strength, compression load is applied to simply supported CFRP columns. Load is applied to the top of the column, as shown in Fig. 4. To create rigid region, nodes are constructed at the top and bottom ends of the section centroid, which are then connected to the section edge through edge nodes. The section's edge nodes are all regarded as dependent nodes. All dependent nodes are connected to independent node, which is constructed at the geometric centroid of the section. As depicted in Fig. 4, the master node at the centroid is used to apply the boundary and loading conditions. Figure 4 shows the chosen boundary conditions for the X, Y, and Z directions.

Table 2 First buckling mode of the FRP columns

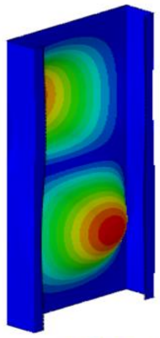
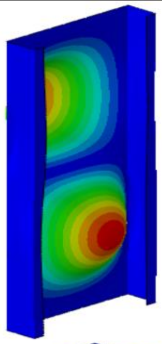
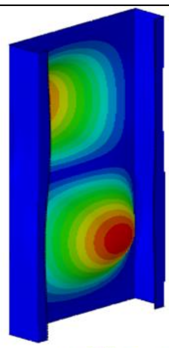
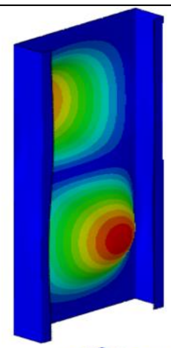
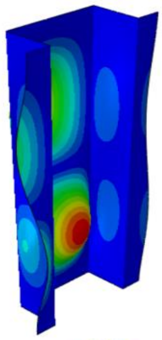
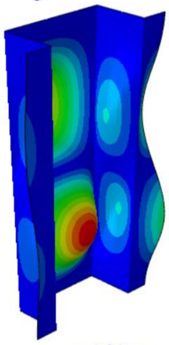
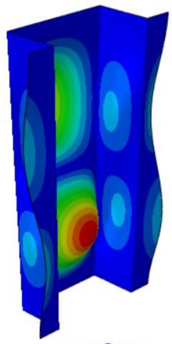
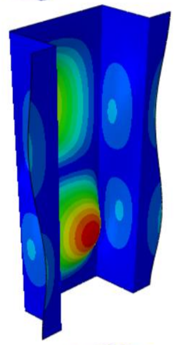
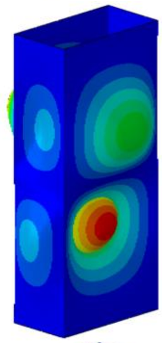
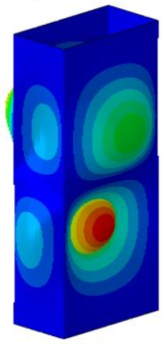
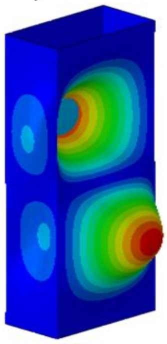
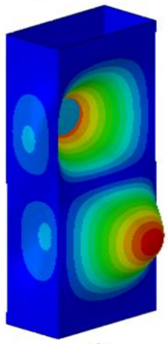
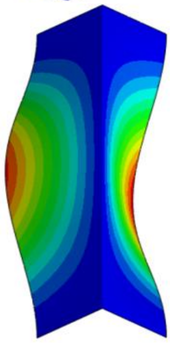
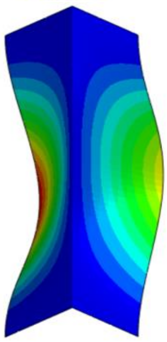
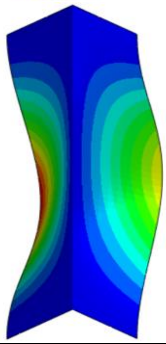
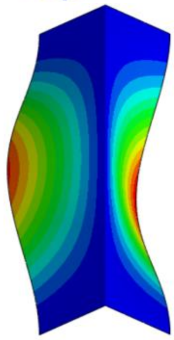
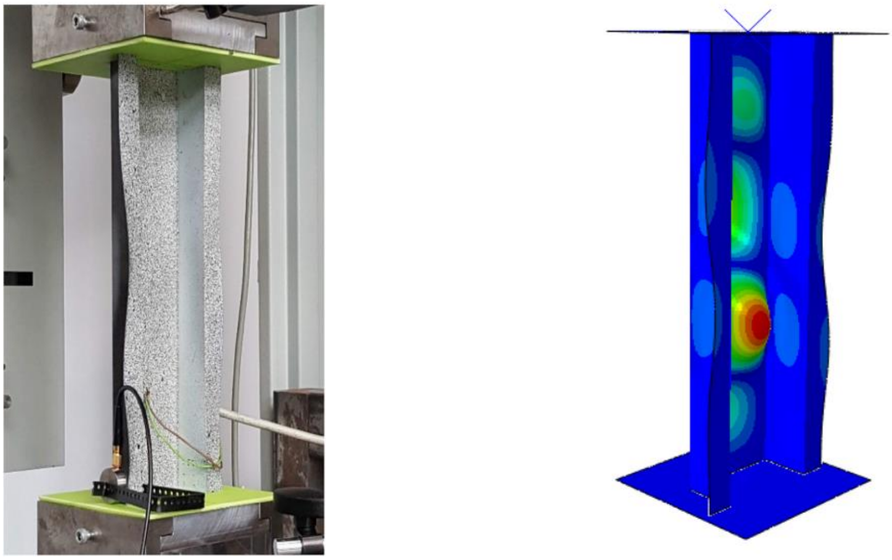
Cross-sectional type	Load eccentricity value (mm)			
	e1		e2	
	10	-10	10	-10
Channel section with lip towards inside (C1)				
Channel section with lip towards outside (C2)				
Box				
Angle				

Table 3 Validation of FE models

b_w x b_h x b_s x t	H (mm)	E_L (GPa)	E_T (GPa)	G_{LT} (GPa)	ν_{LT}	e1 (mm)	e2 (mm)	Buckling loads (Pcr) (kN)		Exp/FEM (g/h)
								Exp[c](g)	FEM[d](h)	
60x30x15x0.84	250	143	5.83	3.8	0.36	0	0	5017	5201	0.96
60x30x15x0.84	250	22.1	10.4	2.1	0.36	0	3	6119	6330	0.96
60x30x15x0.84	250	23.7	10.5	2.2	0.36	0	-10	2757	3057	0.90
60x30x15x0.84	250	23.7	10.5	2.2	0.36	10	0	4973	5133	0.96
								Average/Mean		0.96
								Standard deviation (SD)		0.01

[c]Debski *et al*. (2010), [d]by present study



(a) (b)

Fig. 5 Buckling mode of structure under axial compression: a) experimental, b) numerical.

2.5 Elastic analysis

The cross-section centerline measurements were used to generate the numerical model. The buckling strength of FRP angle columns was calculated using eigenvalue buckling analysis. Table 2 shows the buckling mode determined by elastic analysis.

2.6 Validation

When establishing constraints, material properties and mesh sizes finite element modelling requires additional care. Before the FE model can be employed in the analysis, its accuracy must be verified. Hence, results provided by Debski *et al*. (2020) were utilised to validate the accuracy of the current models of FRP columns. The support conditions used in Debski *et al*. (2020)

Table 4 Details of laminate

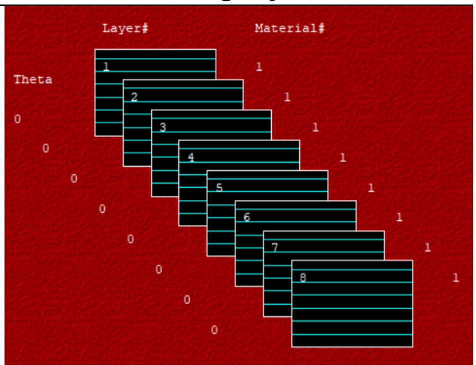
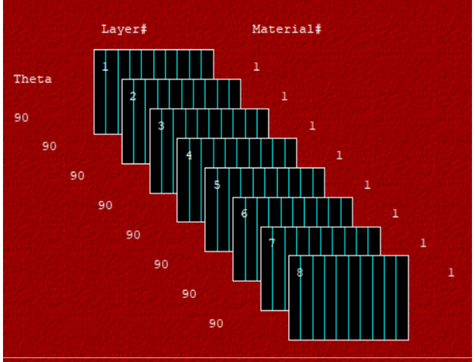
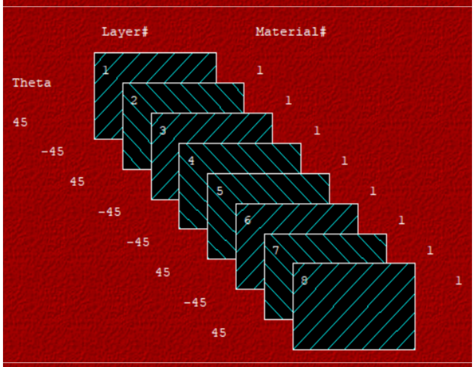
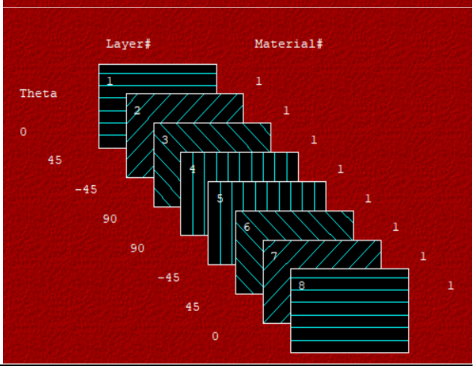
Laminate Id	Order of the plies	Stacking sequence
L1	$[0/0/0/0]_s$	
L2	$[90/90/90/90]_s$	
L3	$[45/-45/45/-45]_s$	
L4	$[0/45/-45/90]_s$	

Table 5 Geometry details

Cross-section type	H	b_w	b_h	b_s	t
C1	750	190	45	15	1.45
C2	250	60	30	15	0.84
box	750	152	152	-	2
Angle	250	50	50	-	2

experimental tests were used to set the boundary conditions of the numerical model. The ends of each column were just held up by rigid plates. The whole model was fixed at the reference points RP, which were in the same place as the centres of gravity of the ball joints in the testing machine's mounting heads. All translational degrees of freedom were limited at the lower reference point, so Ux = Uy = Uz = 0. Also, it couldn't turn around the axis of the column, so URy = 0. Similar boundary conditions were used to describe the upper reference point, except that it could move in the axial direction (Ux=Uz=0 and URy=0), along which the compressive load P was applied. To connect all degrees of freedom, rigid relationships were used to describe the reference points and the plates. The comparison of the buckling findings is shown in Table 3. Fig. 5 compares the failure mode shapes of columns. The predicted buckling stregnth by present study is very close to Debski *et al* (2020) experimental findings. It signifies that the simulated (2020) FRP column models' load application, restrictions, and material attributes are correct. As a result, a parametric analysis with the specified sectional shape, material properties and stacking sequence is performed in this paper.

4. Influence of load eccentricity on critical buckling strength

The load eccentricity and laminate configuration have a substantial impact on the state of stress in the elements, which influences the buckling strength of a column. Fig. 6 depicts the impact of laminate arrangement and load eccentricity on section C1. As the eccentricity e1 increases, the buckling strength does not change noticeably because the rigidity is high in X direction. For all four laminate samples, the maximum increase in buckling strength is seen to be around 1%. On the other hand, a contrasting trend is seen along e2. For L3 case, the highest increase and decrease in buckling strength relative to the axial case are seen at about 60% and 38%, respectively, which mean that the structure rigidity increased and decreased.

Fig. 7 depicts the impact of laminate arrangement and load eccentricity on section C2. The eccentricity along e1 has little significance in this section as well. For the L1 case, the highest buckling coefficient reduction is shown at roughly 5%. Buckling strength is reduced by about 1% in other laminate configurations. Significant variation in buckling coefficient has been seen along e2. For the L3 case, the maximum buckling strength increase, and decrease are measured at roughly 43% and 41%, respectively. When the column subjected to both compression and bending due to eccentricity the coupling stiffness D_{16} and D_{26} will influence the buckling strength hence L3 case provides maximum percentage increase in buckling stregnth incompare to the other laminate cases.

The behavior of FRP box columns under eccentric compression is depicted in Fig. 8. The buckling load reduces as eccentricity increases in both directions, i.e., X and Z. Buckling load

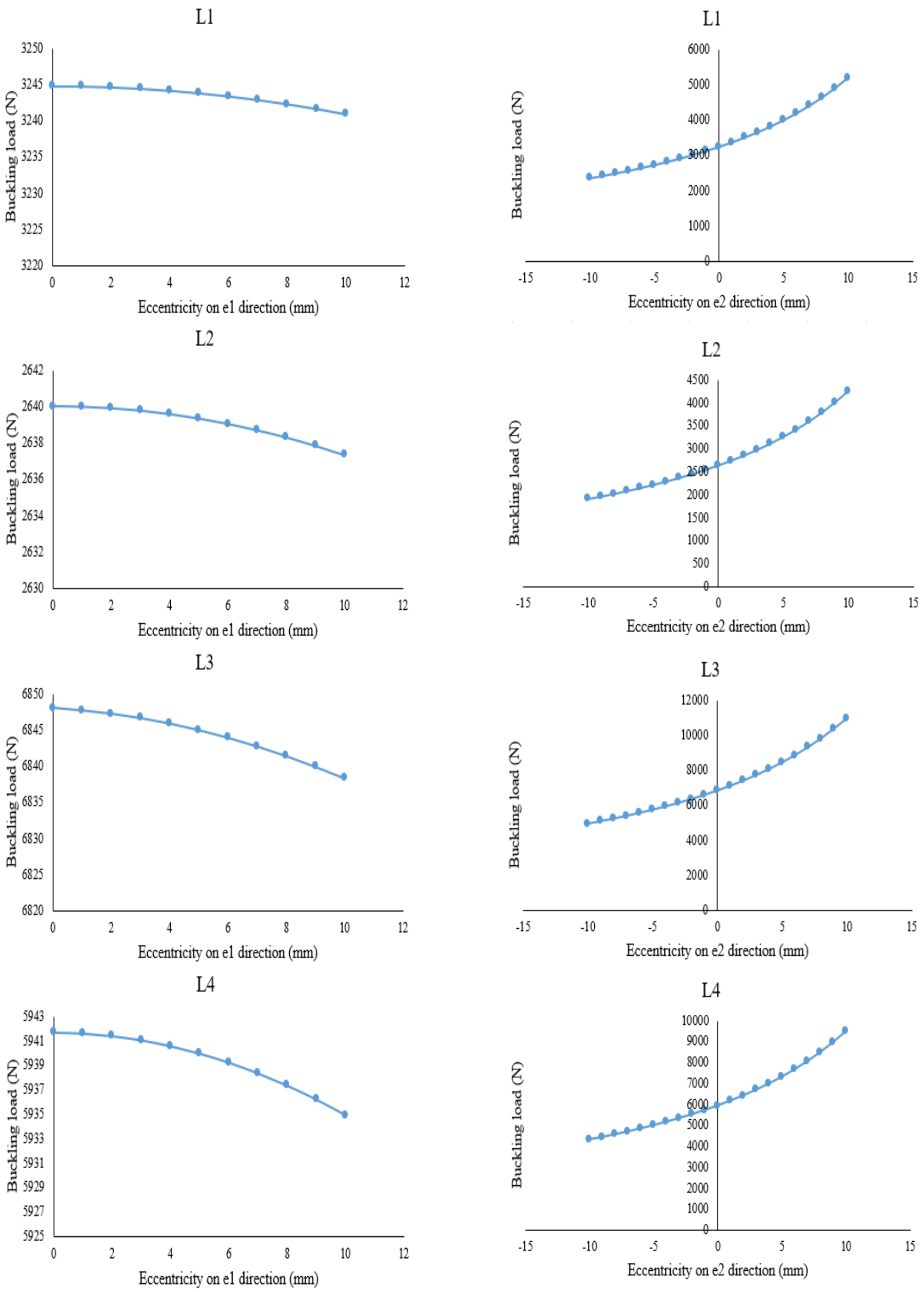


Fig. 6 load eccentricity versus buckling load - C1 section

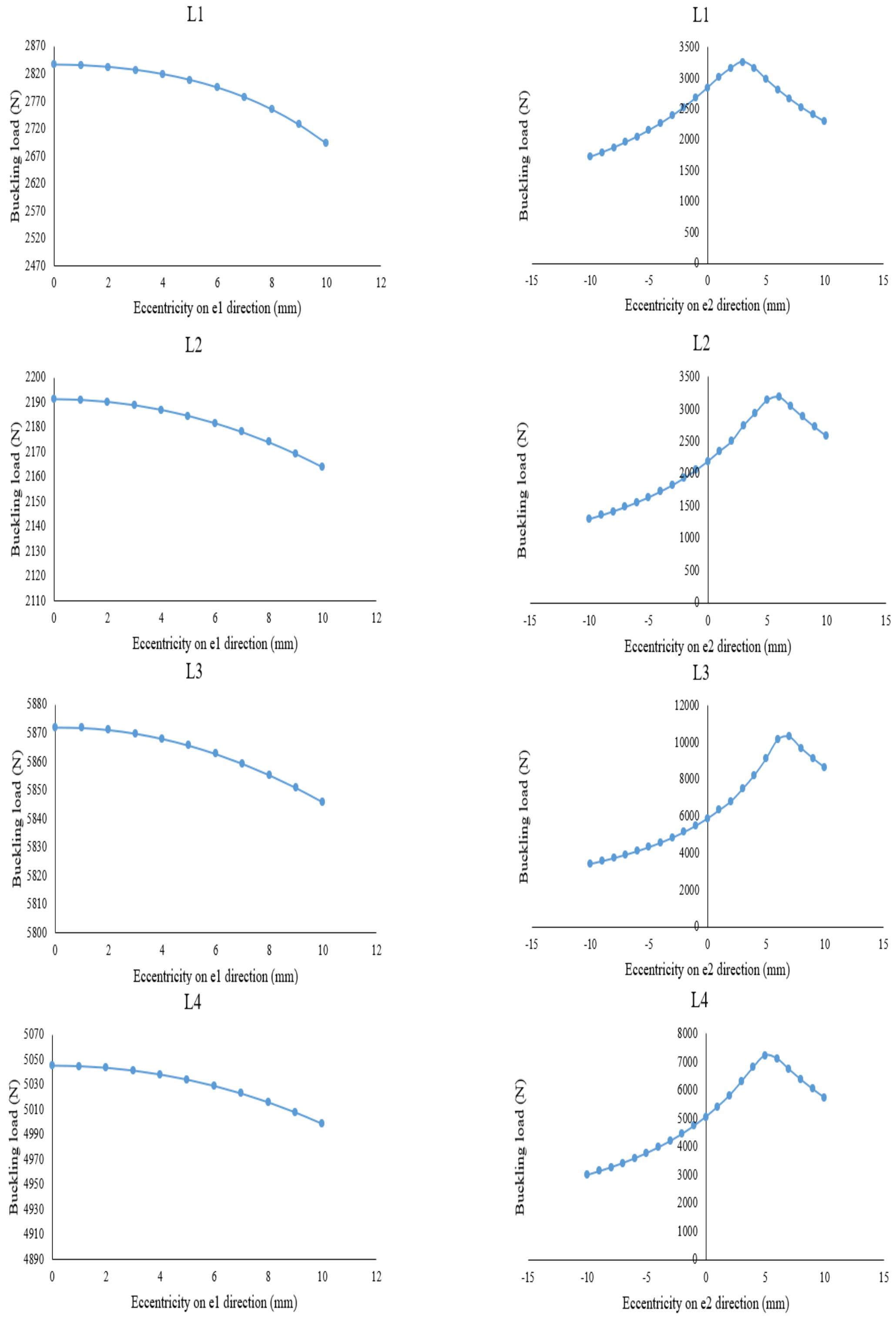


Fig. 7 load eccentricity versus buckling load - C2 section

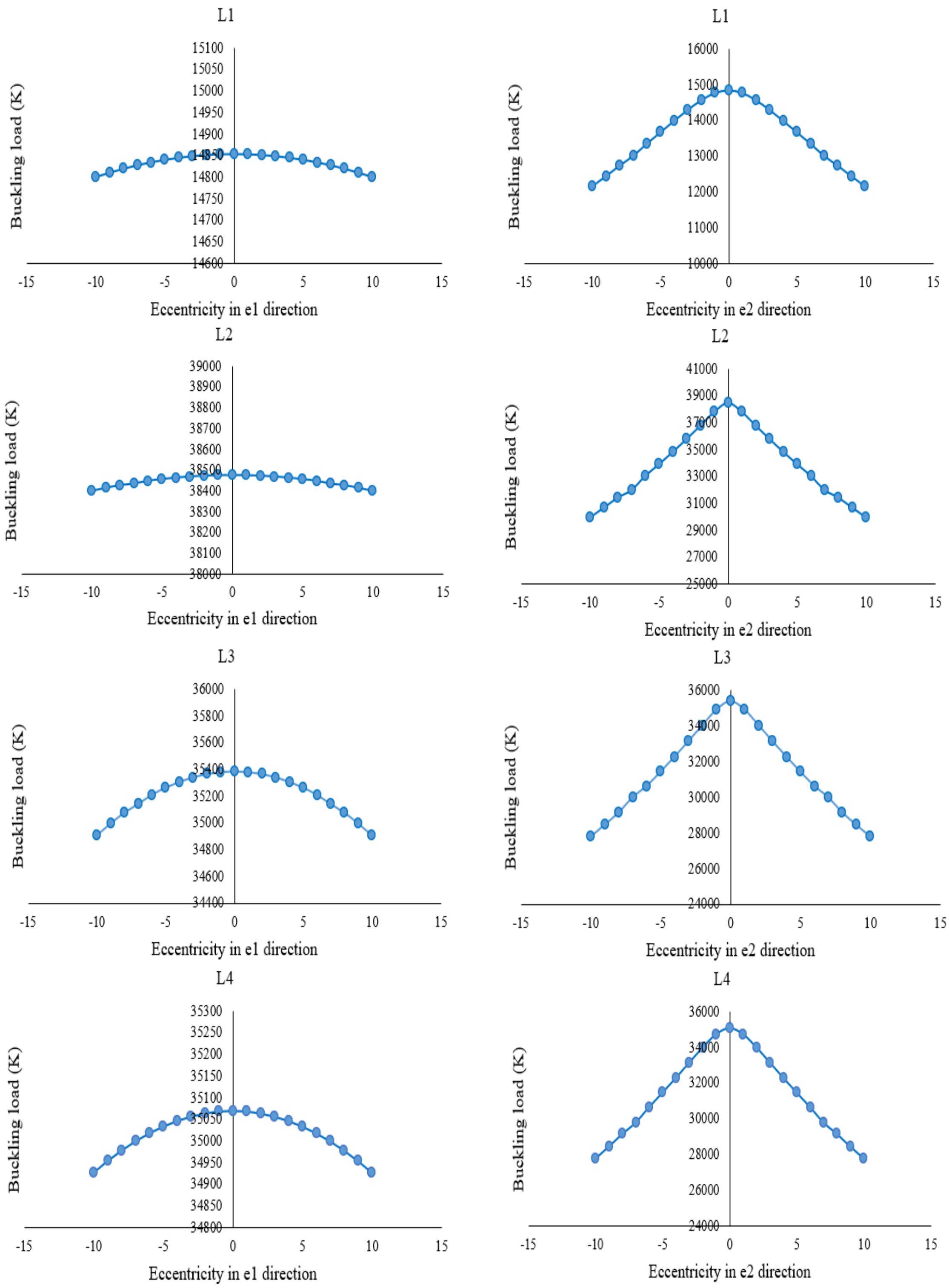


Fig. 8 Load eccentricity versus buckling load for box column

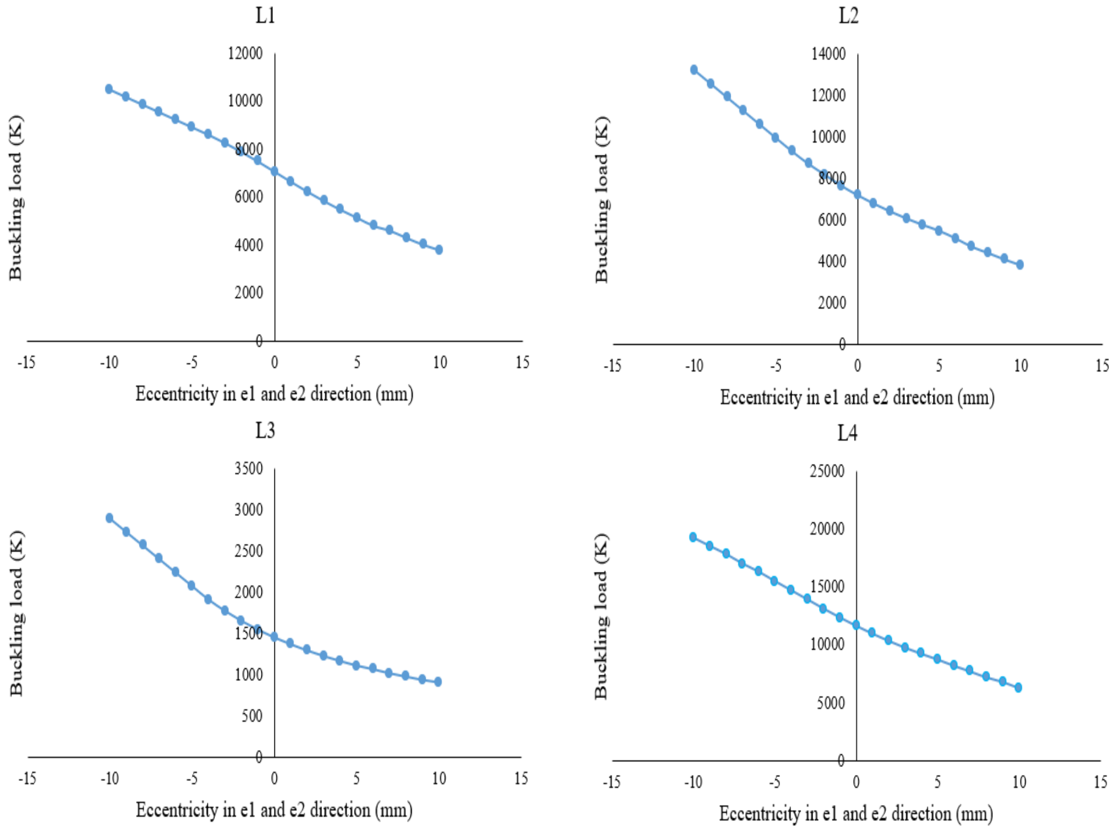


Fig. 9 Load eccentricity versus buckling load for angle column

varies marginally when eccentric force is applied in direction X. In comparison to the axial load scenario, the critical buckling load dropped by 0.5% for the L1, L2, and L4 cases. Comparing the L3 case to the axial load case, the critical buckling load fell by 1.5%. When eccentric force is applied in direction Z, the buckling load changes significantly. In comparison to the axial load case, the critical buckling load for the L2, L3, and L4 cases fell by about 26%. Comparing the L1 case to the axial load scenario, the critical buckling load fell by about 23%.

Fig. 9 shows the buckling load versus with load eccentricity for angle FRP columns. Compared to the axial load case, L1, L2 and L4 laminate case critical buckling load increased and decreased by around 48% and 46%, respectively. L3 case laminate perform better than other laminate cases because it has high coupling stiffness in compare to the other load cases. L3 case critical buckling load increased and decreased by 99% and 35%, respectively.

6. Conclusions

Buckling behavior of FRP columns studied previous also, but most of them considered ideal load conditions. In real operating conditions, buckling strength is significantly affect by various inaccuracies including geometric imperfections and imperfections caused by eccentric load and non-uniform boundary conditions. Particularly, when subjected to eccentric loads, The structure functions in a complex loading state (compression and bending), which causes buckling earlier than anticipated. Thus, using the FEA tool ABAQUS (2011), the current work has investigated the impact of load eccentricity on the buckling behaviour of open and closed profile columns by altering eccentricity in both main and minor axes. Based on the investigation the following qualitative and quantitative trends have been drawn.

C1 and C2 section

• The buckling load varies marginally when the eccentric load is applied in direction X (i.e., towards the higher rigidity of the column section).

◦ For C1 case – The critical buckling strength of all laminate configuration is reduced by 1% with respect to axial load case.

◦ For C2 case - In comparison to the axial load case, the critical buckling strength for the L3 case reduced by 5%, and for the remaining laminate case, it decreased by 1%.

• When eccentric load is applied in direction Z (i.e., parallel to the web of the top-hat profile). The buckling load increased by 60% and decreased by 38% when comparing the C1 case to the axial load case. The buckling load increased by 43% and decreased by 41% when comparing the C2 case to the axial load case.

Box section

• Buckling load varies marginally when eccentric force is applied in direction X and compared to axial load case.

◦ For L1, L2 and L4 case - The critical buckling strength reduced by less than 0.5%.

◦ For L3 case – The critical buckling strength was reduced by 1.5%.

• Buckling load varies significantly when eccentric force is applied in direction Z and compared to axial load case.

◦ The critical buckling load dropped by around 26% for all laminate case.

Angle section

• When the column is subjected to eccentric load, the maximum increase and decrease in buckling strength with respect to axial case is observed 99% and 37%. L3 case laminate perform better than other laminate cases such as L1, L2 and L4.

The aforementioned data demonstrates that eccentric load, depending on its direction with respect to the centre of gravity of the column's cross section, can significantly affect a column's tendency to buckle under compression.

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WT

Nomenclature

H	column length
t_w, t_f	thickness of web and flange
b_w, b_h	width of web and flange
$e1$, $e2$	applied Eccentricity in X and Z direction
$C1$, $C2$	channel section with lip towards inside and outside
E_L, E_T, G_{LT}	lamina modulus
υ_{LT}, υ_{TL}	lamina major and minor Poisson’s ratio
$L1$, $L2$, $L3$, $L4$	laminate id