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Research article

Numerical buckling analysis of carbon fibre‒epoxy composite plates with different cutouts number by finite element method

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Abstract: Composite materials are one of most important engineering structures due to their desirable structural properties like corrosion resistance, high specific strength, specific stiffness, and lightness compared to conventional materials. This article provides numerical study with linear and nonlinear analysis of the influence of thin carbon/epoxy composite plates with rectangular cutouts on the buckling behavior. The aim of current study is to examine the effect of central rectangular cut outs number of single, double, and triple cut outs of rectangular carbon–epoxy composite plates on the maximum buckling load and maximum deflection under natural and post buckling mode. This determination is to evaluate the possibility of employing elastic elements such as thin carbon–epoxy composite plate elements, whose stiffness affected by modifying the laminate cut-outs number at constant total area, where the area of the single cut out, total area of double cut outs, and total area of triple cut outs are equal. The finite element method was adopted to analyse the structure numerically. Furthermore, in order to maintain stable structure operation under post-buckling range, the laminated composite plates were arranged symmetrical lay-up with extension bending couplings. The finding demonstrates that the distribute of cut out area on the composite plate area with rectangular shape at constant total cut outs area lead to increase the maximum load and slightly reduces the maximum deflection, this can be attributed to the improvement of the compression load distribution on the composite plate model.

Keywords: carbon–epoxy composite plates; finite element method; post-buckling; compression test

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1. Introduction

The plates with composite materials are widely employed in aerospace structures, robotic arms, automobiles, and architecture due to their required structural properties like corrosion resistance, high specific strength, specific stiffness, and lightness compared to conventional materials [1,2]. Recently, composite stiffened structures are widely used in different engineering and industrial applications such as aerospace marine structures and bridges due to their lighter weight and environment friendly [3,4]. Therefore, it is essential to understand the behavior of the composite plate structure such as the buckling loads, deflections and modal characteristics and the failure characteristics [5,6]. The buckling load of composite plates is depending on the stiffness of the local bending which subjugated to the fibre orientation, the stacking sequence and the spatial direction. Furthermore, the finite element methods considered an effective approach to evaluate buckling coefficients with taking in account the plate's orthotropic properties [7].

Shirkavand et al. [8] performed an experimental and numerical investigation of composite cylinders with rectangle cutout under buckling mode. The effect of orientation and rectangle cutout size in composite cylinder were the main objectives. The result shows that the cutout with axial direction increase buckling load approximately 8% in comparison with circumferential direction. Ovesy et al. [9] performed numerical study of composite plates with random shape under compressive post-buckling using finite element method and theory of higher order shear deformation. Moreover, finite element method analysis was used to provide the required analysis by employing ANSYS software.

Nevertheless, Hao et al. [10] analyzed the effect of cutouts with the variable-stiffness panels using isogeometric method, by employing the level set method to represent the cutouts. The results showed that the proposed method can provide an accurate buckling load prediction with high rate of convergence and low computational cost for optimizing fibre path. In another investigation the influence of multi-cutouts in curvilinearly stiffened panel have been conducted under hierarchical nondeterministic optimization. The finding reveals that the proposed framework improves the rationality of deterministic design optimization and provides a competitive efficiency and robustness over other nondeterministic approaches [11]. Moreover, an operative framework optimization of cylindrical shells stiffened with cutouts reinforced with curvilinear stiffeners has been adopted to improve the loading path Hao et al. [12]. The investigation proved the effectiveness of the employed framework, comparing to traditional optimizations.

Furthermore, based on support vector regression (SVR) model, laminated composite curved panels with cutout have been investigated under stochastic natural frequency analyses. Meanwhile, the effect of twist angle, cutout sizes and geometrical shape have been carried out. These parameters are enumerated to project the relative importance of different random inputs on natural frequencies [13]. Narayanan and Der Avenessian [14], carried out extensive analysis using the finite element method. Buckling modes corresponding to centrally or eccentrically located cutouts that two buckles are formed when the hole is placed at the extreme end of the compression diagonal, whereas only a single large buckle develops when the hole is located along the tension diagonal. Additionally, the finite element methods have been employed to analyse the probabilistic characterisation for dynamics and stability of laminated composites and laminated soft-core sandwich plates [15,16].

Another studies by Erdem et al. [17] has been carried out the effect of carbon fibre epoxy composite plates with circular cutout at central position under post-buckling analysis. The results indicated that after the buckling analysis the load displacement of the composite plate did not affected by increasing the cutout diameter, meanwhile, the increase in cutout diameter led to decrease maximum failure displacement as well as decrease the maximum damage load. Nonetheless, the stress at the cutout perimeter increased tentatively after the buckling with the vertical displacement incremental.

A numerical and experimental determination was achieved on composite plates to examine the impact of cutout length/thickness ratio on the buckling performance [18]. The results reveal that the buckling loads of the composite plates without cut out are higher than those with cutout. Yidris et al. [19] examine numerically the influence of multiple central circular cut-out on the capacity of the buckling of thin-walled plates. Their analysis revealed that the plates with single cut-out provide higher rate of the shear buckling coefficient than plates with multi circular cutouts. Moreover, increased cut-outs quantity means increasing in perforated area and led to less shear strength in the rectangular plates.

Nevertheless, the rectangular laminated plates have gained more consideration among the different aspects of composite plate structural performance [20,21]. Ghannadpour et al. [22] investigated numerically the buckling analyses of polymer matrix composites plates with cutout. The finite element analysis was adopted to study the effects of cutout on the buckling performance of rectangular laminates with symmetric cross-ply. Kumar and Singh [23] examined the impact of the cutout shape on buckling behaviour of composites plates. The finding indicates that the angle and shape of the cut out are effect significantly on the failure mode. Aydin Komur et al. [24] studied numerically buckling behaviour of composite plates with different cutout using finite element method. The results show that buckling loads are increased by decreasing hole positioned angle and elliptical holes.

Falkowicz et al. [25] performed a numerical investigation on rectangular plates of high strength steel with different cutout sizes under effect of buckling mode The study focuses on the impact of cutout sizes on the elastic properties of the investigated plates. The obtained nonlinear solution with elastic plates operating under higher buckling mode, provide wide range of application. The reason behind that can be attributed to simple selection of the desired structure parameters like rigidity and load carrying capacity.

Falkowicz et al. [26] studied numerically the behaviour of compressed laminate composite plate of carbon-epoxy with central rectangular cutout. The investigation was performed on plates with symmetric laminate with changing the width and height of the cutout geometry and the orientation angle of fibre in a laminate ply. The results reviled that the change in cutout width and heights lead to increase maximum load to 1038.24 and 1095.92 N, respectively. Meanwhile, the change in fibre orientation angle lead to provide higher incremental in the maximum load by approximately 30%.

It appears from the aforementioned investigations that numerous investigations have been conducted the effects of cutouts in composite plates. However, there are a quite few research studies on post and natural buckling performance of composite plates with rectangular cutouts. Nevertheless, studies of composite plates under buckling and post buckling behavior with rectangular cutouts which involve the effects of cutouts number on their natural buckling and post buckling responses are rare to find in literature. In this study, an investigation of buckling and post buckling behaviour was carried out for rectangular carbon-epoxy composite plates with different cutouts number at constant total cutouts area using finite element methods, where, the area of the single cutout, total area of double cutouts, and total area of triple cutouts are equal.

2. Finite element method computations

Finite element method has been used to investigate the composite plates with rectangular cutouts under buckling mode with influence of cutouts numbers. In the numerical procedure, the finite element method was applied using ANSYS [27] to analyse the buckling performance of investigated composite plates at constant total cut-outs area. Moreover, in order to obtain identical results to the results of [26], similar boundary conditions to the experimental conditions must be adopted. Nonetheless, the mechanical properties of the studied composite plate of carbon–epoxy with 60% fibres are shown in Table 1.

Table 1. The mechanical properties of composite plate [26].

Young modulus (GPa)		Tensile strength (MPa)		Shear modulus (GPa)	Shear strength (MPa)	Poisson's ratio	Compression strength (MPa)	
E_1	E_2	F_{TU}		G_{12}	F_{SU}	v_{12}	F_{CU}	
0°	90°	0°	90°	±45°	±45°	0°	0°	90°
131.71	6.36	1867	26	4.18	100.15	0.32	1531	214

The plate of 1.048 mm total thickness had 8 plies with ply orientation [0/−45/45/90/90/45/−45/0]. The relationship between moments (M) and internal loads (N) can be written as Eq 1 based on the Classical Lamination Theory [28–30]:

$$\begin{pmatrix}(N)\\(M)\end{pmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} & 0 & 0 & 0 \\ A_{21} & A_{22} & A_{26} & 0 & 0 & 0 \\ A_{61} & A_{62} & A_{66} & 0 & 0 & 0 \\ 0 & 0 & 0 & D_{11} & D_{12} & D_{16} \\ 0 & 0 & 0 & D_{21} & D_{22} & D_{26} \\ 0 & 0 & 0 & D_{61} & D_{62} & D_{66} \end{bmatrix} \begin{Bmatrix}(\varepsilon^b)\\(k)\end{Bmatrix} = \begin{bmatrix}[A] & [B]\\ [B] & [D]\end{bmatrix} \begin{Bmatrix}(\varepsilon^b)\\(k)\end{Bmatrix} = [K] \begin{Bmatrix}(\varepsilon^b)\\(k)\end{Bmatrix} \quad (1)$$

where *A*, *B* and *D* are stiffness matrices components and defined for the directions of material orientation i,j = 1, 2, 3 are; *A* (extensional), *B* (coupling) and *C* (bending) stiffness matrixes as represented in Eqs 2, 3, and 4, respectively. Additionally (ε^b) represents mid-plane strains, and (κ) is a mid-plane curvature.

$$A_{i,j} = \sum_{k-1}^{n} [\bar{Q}_{ij}]_k (z_k - z_{k-1}) = \sum_{k-1}^{n} [\bar{Q}_{ij}]_k t_k \quad (2)$$

$$B_{i,j} = \sum_{k-1}^{n} [\bar{Q}_{ij}]_k (z_k^2 - z_{k-1}^2) = \sum_{k-1}^{n} [\bar{Q}_{ij}]_k t_k \, z_k^c \quad (3)$$

$$D_{i,j} = \frac{1}{3} \sum_{k-1}^{n} [\bar{Q}_{ij}]_k (z_k^3 - z_{k-1}^3) = \sum_{k-1}^{n} [\bar{Q}_{ij}]_k \left(t_k (z_k^c)^2 + \frac{t_k^3}{12} \right) \quad (4)$$

where *n* and *k* are the total plies number and the existing plies number, $\bar{Q}_{ij}$ is the transformed reduced stiffness, z_k is a distance from the top to the plate mid-plane, t_k is ply thickness, z_k^c is a distance between the mid plane to the centre of gravity [31,32].

The Tsai–Wu damage criterion was used to model the damage behavior during the buckling state. Tsai–Wu failure criteria is a stress-based and state of plane stress for an orthotropic lamina, it can be written as Eq 5:

$$\left(\frac{1}{X_T} - \frac{1}{X_C}\right)\sigma_1 + \left(\frac{1}{Y_T} - \frac{1}{Y_C}\right)\sigma_2 + \frac{\sigma_1^2}{X_T X_C} + \frac{\sigma_2^2}{Y_T Y_C} + \frac{\tau_{12}^2}{S_{12}} + 2F_{12}\sigma_1\sigma_2 \le 1 \tag{5}$$

where F_{12} is an interaction coefficient of the product of σ_1 and σ_2 respectively. The damage which began at $\delta y = \sim 1$ mm progressed horizontally with the increase of displacement [33].

2.1 Numerical analysis and mesh independency

Discretization of the investigated plate is achieved utilizing shell elements with integration of eight nodes, each element has six degrees of freedom on each node. However, the flexible strains in these plate shell elements are estimated as a function of the angular displacement while strains that are in accordance with the state of the membrane are estimated as a function of the linear displacement [34]. In the present analysis, elements with the second order shape function has been used. The investigation involved performing a numerical analysis of non-linear stability of a uniformly compressed plate, where a higher mode of buckling was forced to ensure stable operation of this structure in the post-buckling state. In order to examine the desired buckling mode, the plate had a central cut-out, the geometric dimensions of which had a direct effect on the plate's stability and operation in the post-buckling state. As a result, they affected the characteristics of the plate's post-buckling equilibrium path in the elastic state. This way of shaping elastic properties of plates is particularly important if such structures are to be used for various designs [35].

Figure 1 illustrates the mesh of the numerical model with the applied boundary condition. The existing case boundary conditions that represented the expressed plate support are determined by obstructive the nodes kinematic degrees of freedom that positioned on the plates at top and bottom edges. The FEM model is achieved by implementing consistent load to the top edge of the plate. Furthermore, the numerical analysis suspected that the rang of the operation elastic element is adjust to be less than the yield point and it does not change the original element rigidity. Therefore, the calculation continues until it reaches the yield point, that is, Re = 1180 MPa. The structure's operation range is determined by elastic material and linear models. Numerical calculations are carried out in two steps, the first step involves checking the structure buckling state. Firstly, is to examine the structure's buckling state. The solution of this case has been to determine the buckling load and associated modes of losing stability. In order to estimate the torsional and flexural buckling mode, three natural buckling modes are analysed for each case, to guarantee stable structural operation after flexural buckling. Secondly, the calculation involves solving the nonlinear stability problem. Computing is achieved using models with geometric imperfections that compatible with torsional and flexural buckling modes [36]. Moreover, the amplitude of the preliminary imperfection is set to 0.1 of the thickness of the plate. Furthermore, Tsai–Wu standard was effectively employed to investigate the failure load of the compressed composite plate for all examined cases in present research [19].

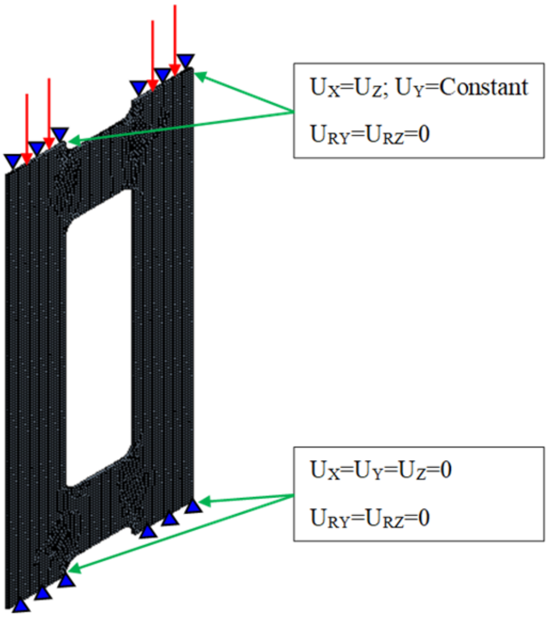

Figure 1. Discrete model of composite plate with boundary condition.

The geometrical models of the investigated composite plates with multi rectangular cutouts are shown in Figure 2, where the area of the single cut out, total area of double cut outs, and total area of triple cut outs are equal.

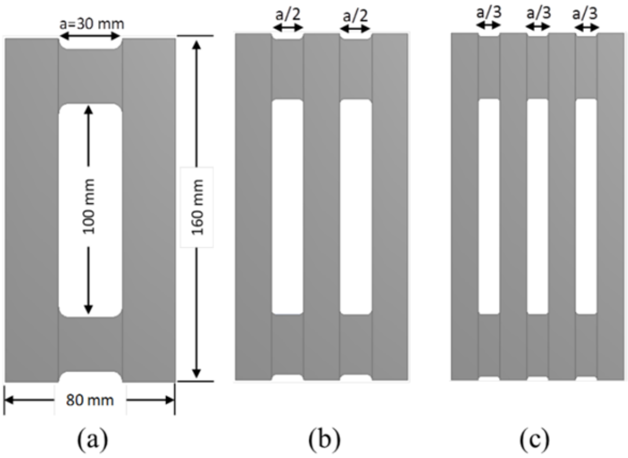

Figure 2. Geometries of simulated composite plates with cut-outs (a) single cut-out, (b) double cut-outs, and (c) triple cut-outs.

Several different element size of 2.0, 1.5, 1.0 and 0.5 that represented as nodes number of 18392, 32047, 69224, and 106401 have been carried out to confirm that the estimated results are grid independent. Its illustrated in Figure 3 that increasing the element size do not change significantly the load and maximum deflection of the tested model of the composite plate. Therefore, the grid consisted of element size of (1.0) which represented as nodes number of (69224) has been selected for the present study as illustrated in Figure 3. Moreover, for all the studied geometries the element size of 1.0 has been adopted for the current calculation.

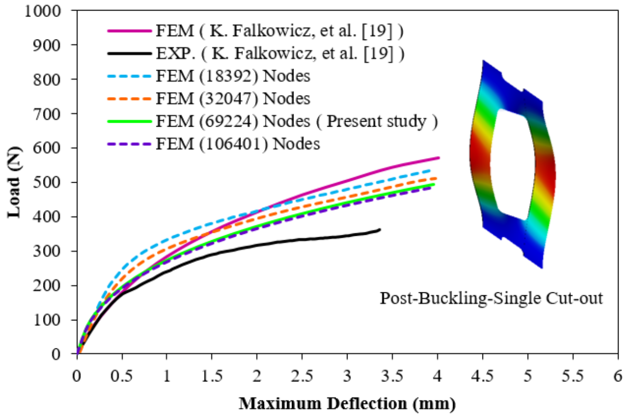

Figure 3. Grid independent tests of rectangular composite plate with single cutout.

3. Results and discussion

For accurate natural and post-buckling calculation, nonlinear analysis was adopted on the thin carbon/epoxy composite plates with single, double and triple cut outs at constant total cut outs area. Hence, the area of the single cut out, total area of double cut outs, and total area of triple cut outs are equal. In order to validate the present numerical results, a comparison of maximum load with maximum deflection has been adopted under identical boundary conditions with experimental and numerical study of Falkowicz et al. [26] as illustrated in Figure 4. The results of the composite plate with single cutout under post buckling technique demonstrated considerable agreement with 13.3% maximum deviation compared with Falkowicz et al. [26] as shown in Figure 4a. Furthermore, Figure 4b display verification of the contour results to clarify the agreement of the pattern of natural and post-buckling behaviour with Falkowicz et al. [26]. The graphical results clarify significant consistent in stress distribution and deformation on the composite plate area with Falkowicz et al. [26]. Therefore, the models are verified and valid to be employed in the present investigation.

Figure 5 displays numerical results for three various geometries of carbon/epoxy composite plates with single, double and triple cut outs under buckling analyses. Furthermore, Figure 5a shows the effect of increase cut outs number with constant total cut outs area on maximum load and deflection under natural buckling analysis. Meanwhile, the influence of multi rectangular cutouts at constant cutouts total area under effect of post buckling mode is illustrated in Figure 5b. The numerical results reveal that the increase in cut outs number at constant cutout area have a considerable impact on critical load for both types of buckling as well as provide wide range of deflection. Nonetheless, the stress increased tentatively at the cutout perimeter and middle region of the composite plate after the buckling with the applied load incremental.

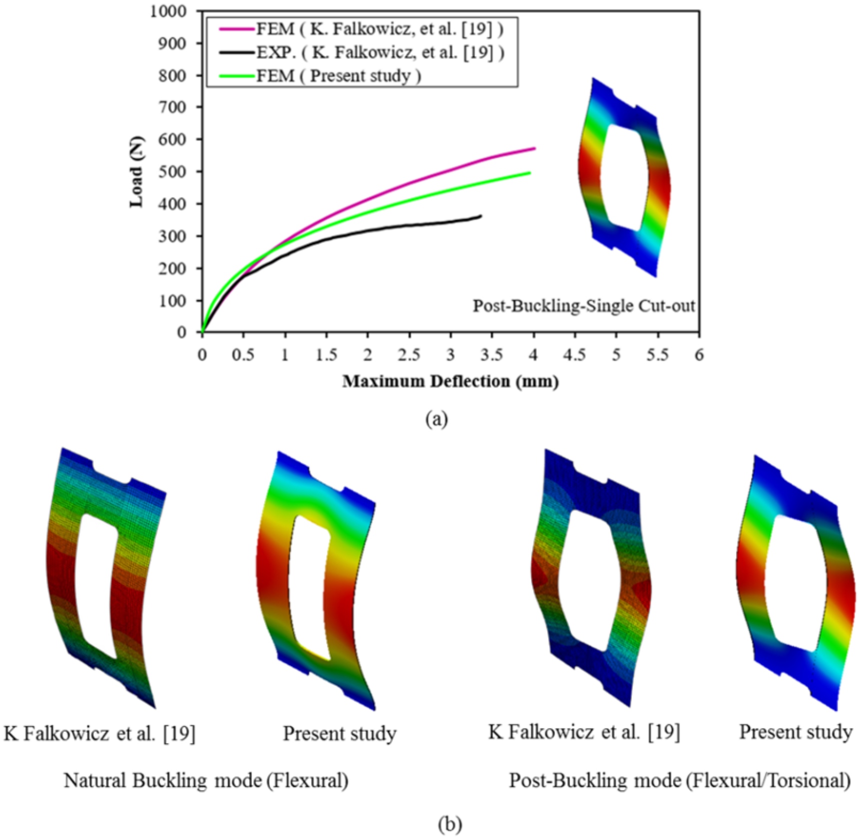

Figure 4. Results validation of the composite plate with single cut-out. (a) post-buckling result validation of carbon/epoxy composite plate, (b) buckling modes.

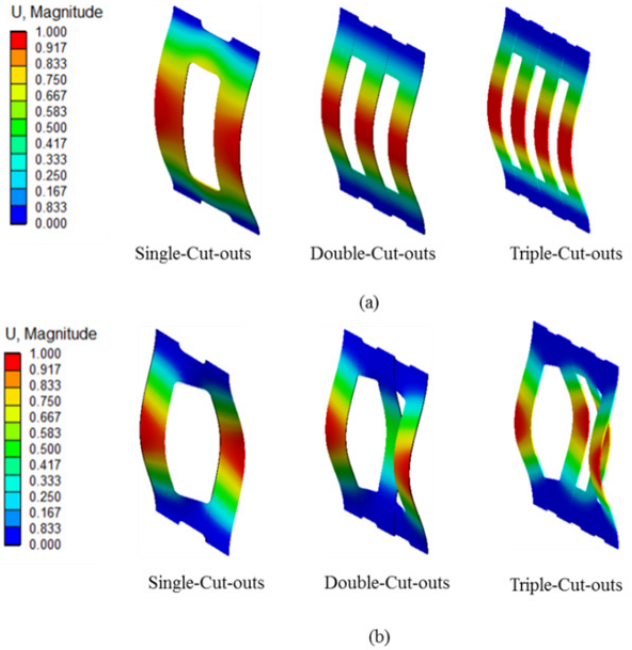

Figure 5. Buckling modes of carbon/epoxy composite plates. (a) natural-buckling modes, (b) post-buckling modes.

As Figure 6 shows, there is a significant difference between the natural and post buckling of single cutouts, which is consistent with the finding of Falkowicz, et al. [26,37]. The finding of composite plate with single cut out provides evidence that the applied load increases until reached maximum load of 223 N and maximum deflection of 4.87 mm under natural buckling analysis. Meanwhile, in post buckling analysis, the maximum load is 494.98 N and the maximum deflection is 3.95 mm. The presented results indicated that the post buckling technique provides 54.93% higher load carrying capacity comparing with natural buckling analysis. Furthermore, the maximum deflection of the composite plate with single cut out under post buckling analysis reduced approximately 18.9% comparing with natural buckling analysis.

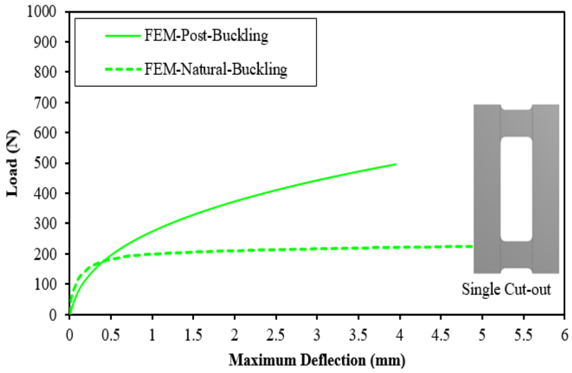

Figure 6. Load deflection comparison under natural and post buckling for single cut out.

Similarly, in Figure 7, the natural and post buckling analyses are presented to clarify the effect of using composite plate with double cut outs at constant total cutout area. The results demonstrate that the maximum load and maximum deflection are 253.95 N and 5.46 mm, respectively under natural buckling analysis. Nonetheless, the results of composite plate with double cut outs at constant total cutout area under post buckling analysis show that the maximum load and maximum deflection are 647.6 N and 4.61 mm respectively. That’s mean the post buckling mode enhance the load carrying capacity approximately 60.79% in comparison with natural buckling mode. Meanwhile the maximum deflection decreased approximately 15.57% comparing to natural buckling mode.

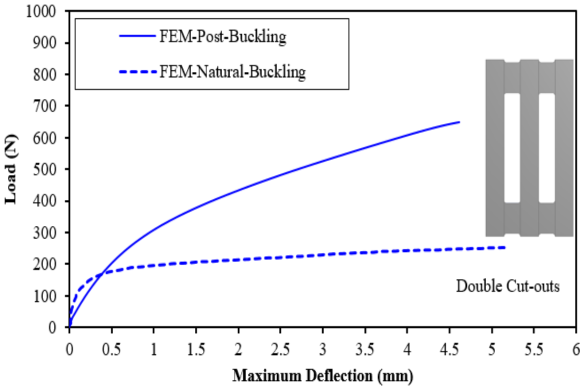

Figure 7. Load deflection comparison under natural and post buckling for double cut outs.

Correspondingly, the results in Figure 8, illustrate the effect of composite plate with triple cut outs at constant total cut out area on the buckling performance of natural buckling and post buckling modes. The finding reveals that the natural buckling load on composite plate with triple cut outs increased gradually to reach maximum load of 305.8 N with maximum deflection of 5.96 mm using natural buckling. Moreover, the results in Figure 8, demonstrate that the post buckling load increased on composite plate with triple cut outs to reach maximum load of 858.4 N and maximum deflection of 5.26 mm. furthermore, the most clear result to arise from this results is that the post buckling mode provides higher load carrying capacity approximately 64.37% than the natural buckling load and reduced the maximum deflection approximately 11.75% compared with the natural buckling load.

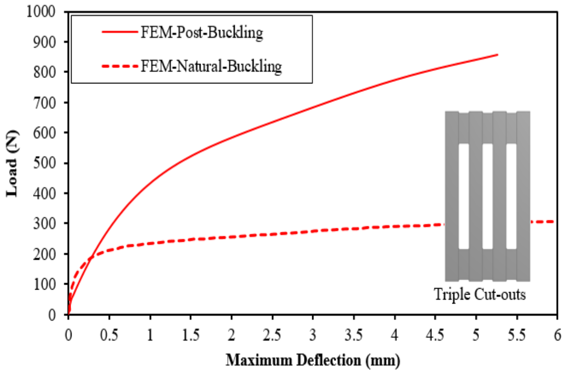

Figure 8. Load deflection comparison under natural and post buckling for triple cut outs.

In Figure 9, demonstrates a comparison of composite plate with different cut outs number under natural buckling. Furthermore, the composite plate with double cut outs offers approximately 12.19% increasing in maximum load and 10.81% maximum deflection comparing to the composite plate with single cut out under natural buckling technique. Meanwhile, the composite plate with triple cut outs provides approximately 18.29% increasing in maximum load and 27.08% maximum deflection comparing to the composite plate with single cut out under natural buckling technique. There is a clear trend of increasing maximum deflection and maximum load with increase cut outs number at constant total cut outs area under natural buckling analysis.

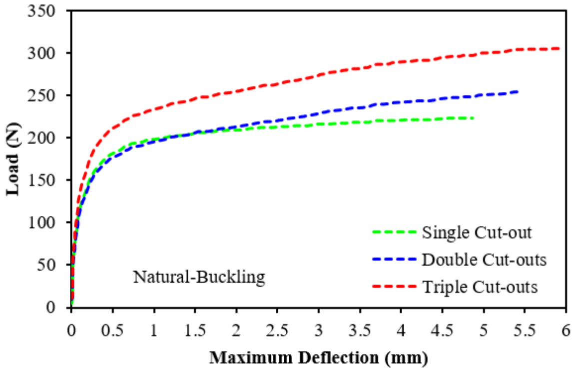

Figure 9. Comparison of different cut outs number under natural buckling.

Similarly, Figure 10 illustrates the influence of increase cut outs number on post buckling performance at constant cutouts total area. The finding demonstrates that the composite plate with double cut outs provides about 23.58% increasing in load carrying capacity and 14.3% maximum deflection comparing to the composite plate with single cut out under post buckling mode. Nevertheless, the composite plate with triple cut outs provides approximately 42.35% increasing in load carrying capacity and 24.9% maximum deflection comparing to the composite plate with single cut out under post buckling technique. The finding demonstrates that the distribute of cut out area on the composite plate area with rectangular shape lead to increase the load carrying capacity and slightly reduces the maximum deflection, this can be attributed to the improvement of the compression load distribution on the composite plate model.

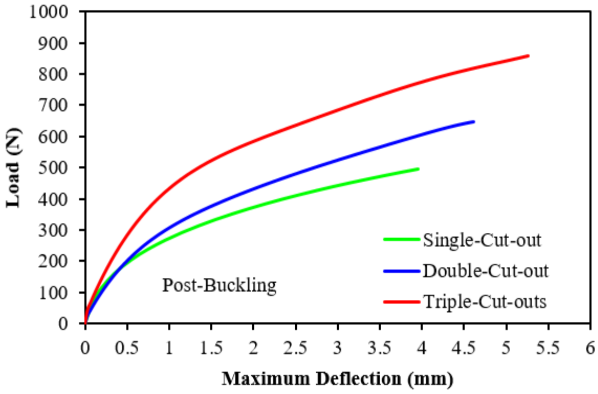

Figure 10. Comparison of different cut outs number under post buckling.

In addition, a FEM analysis of the critical and post buckling states was performed to determine the effect of cut-out geometry on the critical load and stiffness of the structure in the post buckling range. The numerical critical buckling loads obtained from the linear buckling analysis in the first step of the numerical solution are given in Figure 11. The increase in the numerical critical buckling load of the triple cutouts sample under post-buckling is 39.8% according to the single cutout sample. Meanwhile, the increase in critical buckling load is 17.5% under natural buckling of the triple cutouts sample comparing with the single cutout sample.

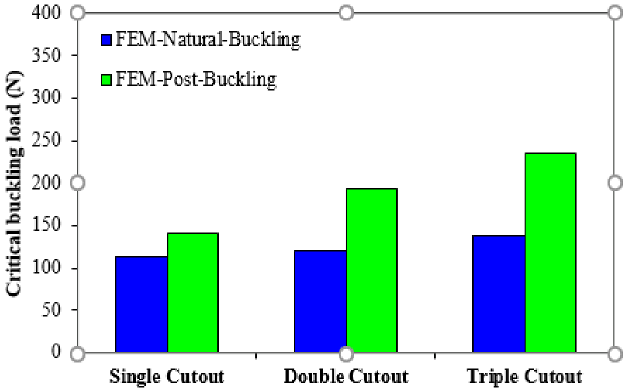

Figure 11. Numerical failure behavior of buckled composite plate in lateral direction.

4. Conclusion

In this study, an investigation of natural buckling and post buckling behaviour was carried out for rectangular carbon-epoxy composite plates with different cutouts number at constant total cutouts area using finite element methods. The current investigation was performed to estimate the impact of cut outs number at constant total cut outs area under natural and post buckling analysis. The results of the numerical simulation indicate that the increasing of cut outs number led to increase maximum buckling loads and reduced the maximum deflection at constant total cut out area. Nevertheless, the composite plate with triple cut outs provides approximately 42.35% increasing in load carrying capacity and 24.9% maximum deflection comparing to the composite plate with single cut out under post buckling technique. One of the important results to arise from this investigation is that the distribute of cut out area on the composite plate area with rectangular shape lead to increase the load carrying capacity and slightly reduces the maximum deflection, this can be attributed to optimize the distribution of compression load on the composite plate model. Further investigation and experimentation into carbon/epoxy composite plates is strongly recommended. A number of possible future studies using the same geometries and boundary conditions are apparent. However, it would be motivating to evaluate the impact of different composite material on the post buckling performance with flexural torsional mode.

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Conflict of interests

The authors declare no conflict of interest.

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