On the thermal buckling behaviour of laminated composite plates with cut-outs

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Abstract: In this work, the thermal buckling behaviour of laminated plates with rectangular cut-outs is studied using the finite element method. Based upon the classical plate theory, the used finite element is a combination of a linear isoparametric membrane element and a high precision rectangular Hermitian element. After validating the results obtained by the finite element, a parametric study is made using three types of materials commonly used in the industry, namely: the T300/5208 Graphite/Epoxy, the AS4/3501-6 Graphite/Epoxy and the E-glass/Epoxy. The study was about the effect of the size of the cut-outs, the boundary conditions, the stacking sequence and the stress resultants distribution on the critical buckling temperature. The study showed that the critical buckling temperature is strongly affected by the discussed parameters.

1. Introduction

The use of composites materials is growing up compared to the traditional materials, basically in all the industrial domains where we need powerful and lightweight structures (Gill et al. 2013, Ounis et al. 2014, Ounis and Balehouane (2016)and Belarbi et al. 2016). Those structures are often facing serious thermal loads due to the aerodynamic heating, pressure or friction (Thornton 1996). Under certain boundary conditions, thermal loads may generate thermal stresses able to cause the thermal buckling phenomenon of composites structural components (Jones 2006).

The composite structures (e.g. plates, shells) are frequently equipped with holes of various shape and dimension, especially in aeronautic and aerospace structures, for the need of weight savings, venting or as access ports for mechanical and electrical systems (Chen et al. 1991, Ko 1998). The existence of such singularities in composite structures introduces load-free boundary conditions that cause the stress field to be non-uniform (Topal and Uzman 2010), which may affect the thermal buckling behaviour of the structures.

In the literature, we can distinguish the work of Chang and Shiao (1990) where the thermal buckling behaviour of circular isotropic plates and square anti-symmetric angle-ply laminated plates with circular holes under uniform temperature rise was investigated. The authors presented a closed form solution based on the classical plate theory to analyze the circular isotropic plates and a finite element solution based on the high order shear deformation theory for the laminated plates. Then, Chen et al. (1991) studied the thermal buckling of anti-symmetric laminates having circular holes subjected to uniform or non-uniform temperature distribution. In order to include the effect of the transverse shear deformation, the first order shear deformation theory is used. Noor et al. (1994) presented a study on the thermomechanical buckling of multi-layered composite panels with central circular cut-outs. The authors used a mixed formulation based on the first order shear deformation theory. Thereafter, Kim and Noor (1996) analysed the buckling and postbuckling of composite panels with circular cut-outs subjected to various combinations of mechanical and thermal loads. The authors, also, analysed the buckling and postbuckling of composite panels with central circular cut-outs subjected to combined shear edge and temperature change (Noor and Kim 1996). Avci et al. (2005b) presented the thermal buckling of symmetric and anti-symmetric cross-ply laminated hybrid composite plates with a circular hole and the thermal buckling of rectangular laminated plates with hole (Avci et al. 2005a). The authors used an eight-nodded finite element based on the first order shear deformation theory. Using the same finite element as (Avci et al. 2005a, Avci et al. 2005b), Şahin (2005) studied the thermal buckling of symmetric and anti-symmetric angle-ply laminated hybrid composite plates with a circular hole. In 2014,Shaterzadeh et al. (2014) studied the thermal buckling behaviour of symmetric and anti-symmetric laminated plates having central and eccentric circular cut-outs.

All the aforecited works dealt with composite plates having only circular cut out. Unfortunately, the literature has not given much attention to the thermal buckling of laminated plates with rectangular cut-out. At the author's best knowledge, there is only the work of Topal and Uzman (2010) where it was about the

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effect of rectangular and circular cut-outs on thermal buckling load optimization of angle-ply laminated thin plates.

The aim of this paper is to study the thermal buckling behaviour of thin laminated plates, with rectangular cut-outs under uniform temperature distribution, using a finite element, previously, developed by the authors (Ounis 2015, Ounis et al. 2014, Tati and Abibsi 2007). The finite element is a combination of a linear isoparametric membrane element and a high precision rectangular Hermitian element.

Furthermore, in order to study the effect of anisotropy on the thermal buckling behaviour of laminated composite plates with rectangular cut-outs, three types of materials commonly used in the industry, namely: the T300/5208 Graphite/Epoxy, the AS4/3501-6 Graphite/Epoxy and the E-glass/Epoxy, have been selected. Thus, a parametrical study is conducted to examine the effect of the cut-out size, boundary conditions, stacking sequences and the stress resultants distribution on the critical buckling temperature of such structures.

2. Theoretical formulation

The displacement field according to the classical laminated plate theory, based on the Kirchhoff assumptions, is given by the following:

$$\begin{aligned} U(x,y,z) &= u_0(x,y) - z\frac{\partial w}{\partial x} \\ V(x,y,z) &= v_0(x,y) - z\frac{\partial w}{\partial y} \\ W(x,y,z) &= w_0(x,y) \end{aligned} \tag{1}$$

Where u_0, v_0, w_0 are the mid-plane displacement components of the plate. The strain-displacement relations, including the large deformations, can be determined as:

$$\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} = \begin{Bmatrix} \dfrac{\partial u}{\partial x} + \dfrac{1}{2}\left(\dfrac{\partial w}{\partial x}\right)^2 \\ \dfrac{\partial v}{\partial y} + \dfrac{1}{2}\left(\dfrac{\partial w}{\partial y}\right)^2 \\ \dfrac{\partial v}{\partial x} + \dfrac{\partial u}{\partial y} + \dfrac{\partial w}{\partial x}\dfrac{\partial w}{\partial y} \end{Bmatrix} + z\begin{Bmatrix} -\dfrac{\partial^2 w}{\partial x^2} \\ -\dfrac{\partial^2 w}{\partial y^2} \\ -2\dfrac{\partial^2 w}{\partial x \partial y} \end{Bmatrix} = \underbrace{\left\{\varepsilon_{\mathrm{L}}^0 + \varepsilon_{\mathrm{NL}}^0\right\}}_{\{\varepsilon\}} + z\{\kappa\} \tag{2}$$

It is known that the thermal stresses are not caused by external loads but are the consequences of restrained thermal distortion (Shiau et al. 2010). The stress-strain relations of the composite laminated plate subjected to temperature rise ΔT, for k^{th} layer, are given by

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix}_k = \left[\bar{Q}_{ij}\right]_k \left(\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix}_k - \Delta T \begin{bmatrix} \alpha_x \\ \alpha_y \\ \alpha_{xy} \end{bmatrix}_k \right) \tag{3}$$

Where $\bar{Q}_{ij}$ is the reduced stiffness matrix for principal material directions, α_x, α_y and α_{xy} are the transformed thermal expansion coefficients. The forces and moments resultants are related to the mid-surface strains and to the curvatures by

$$\begin{bmatrix} N \\ M \end{bmatrix} = \begin{bmatrix} [A] & [B] \\ [B] & [D] \end{bmatrix} \begin{bmatrix} \varepsilon^0 \\ \kappa \end{bmatrix} - \begin{bmatrix} N^{\mathrm{T}} \\ M^{\mathrm{T}} \end{bmatrix} \tag{4}$$

Where [A], [B] and [D], denote the extensional, coupling and bending rigidity matrix, respectively, those can be defined by

$$\{A,B,D\}^{\mathrm{T}} = \int_{-h/2}^{h/2} \left[\bar{Q}_{ij}\right]_k \left(1,z,z^2\right) \mathrm{d}z \tag{5}$$

The thermal force and thermal moment resultants are defined as

$$\left\{N^{\mathrm{T}}, M^{\mathrm{T}}\right\}^{\mathrm{T}} = \int_{-h/2}^{h/2} \left[\bar{Q}_{ij}\right]_k \left[\Delta T\{\alpha\}^{\mathrm{T}}\right](1,z)\mathrm{d}z \tag{6}$$

The total potential energy of laminated plate subjected to thermal loading is given by

$$\begin{aligned} \Pi = \frac{1}{2}\int\int_{-1}^{1} \Big(& \{\varepsilon_L^0\}^{\mathrm{T}}[A]\{\varepsilon_L^0\} + \{\varepsilon_L^0\}^{\mathrm{T}}[B]\{\kappa\} + \{\kappa\}^{\mathrm{T}}[B]\{\varepsilon_L^0\} + \{\kappa\}^{\mathrm{T}}[D]\{\kappa\} \\ & -2(\{\varepsilon_L^0\}^{\mathrm{T}}[N^{\mathrm{T}}] + \{\kappa\}^{\mathrm{T}}[M^{\mathrm{T}}]) + \{\varepsilon_{\mathrm{NL}}^0\}[N^{\mathrm{T}}] \Big)\, dxdy \end{aligned} \tag{7}$$

A finite element which was previously developed by the authors is used in this study(Ounis et al. 2014).The used element is a combination of an isoparametric membrane quadrilateral element and a first order Hermitian rectangular plate element of high degree of accuracy. The element has 4 nodes of 8 degrees of freedom (DOF) each (Ounis et al. 2014). The Cartesian and intrinsic coordinates of the laminated plate are shown in Fig. 1.

Due the existence of cut-outs, the thermal stresses are non-uniformly distributed over the plate. Therefore, it will be necessary to determine the distribution of membrane forces as a first step in this analysis.

After assembling the finite element stiffnesses and load vectors and setting the second variation of the strain energy to zero, the standard eigenvalue problem is obtained:

$$[K]\{X\} + \lambda[K^G]\{X\} = 0 \tag{8}$$

Where $[K]$, $\{X\}$ and $[K^G]$ are the global stiffness matrix, the global displacement vector and the global geometry matrix, respectively.

3. Numerical results

3.1. Finite element validation

Although, the finite element has been already validated in a previous paper (Ounis et al. 2014), more study cases on the thermal buckling behaviour of isotropic and laminated composite plates are analyzed in the present work. Table 1 shows the boundaryconditions forwhich the numerical results have been

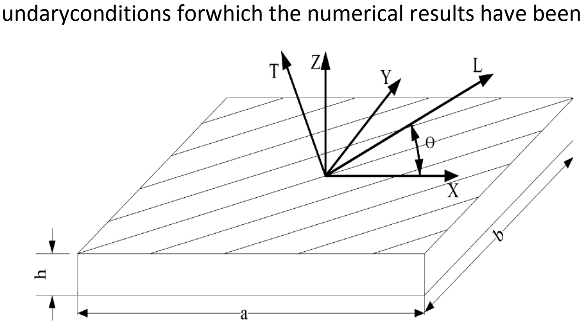


Fig. 1. Geometry and coordinate systems of rectangular laminated composite plate.

Table 1. Boundary conditions.

Boundary conditions (Abbreviations)	Restrained edges
Fully Simply supported (SS)	$u = w = \partial w / \partial y = 0, x = \pm a / 2$ $v = w = \partial w / \partial x = 0, y = \pm b / 2$
Fully Clamped (CC)	$u = v = w = \frac{\partial w}{\partial x} = \frac{\partial w}{\partial y} = \frac{\partial^2 w}{\partial x \partial y} = \frac{\partial^2 w}{\partial x^2} = \frac{\partial^2 w}{\partial y^2} = 0$
Clamped-Simply supported (CS)	clamped at $x = \pm a / 2$, simply supported at $y = \pm b / 2$

obtained, where CC, SS and CS, respectively indicate: clamped, simply supported and clamped-simply supported boundary conditions. The materials used in this study are listed in table 2, namely: the T300/5208 Graphite/Epoxy, the AS4/3501-6 Graphite/Epoxy and the E-glass/Epoxy.

Table 3 shows the critical buckling temperature of isotropic square plates under simply supported and clamped boundary conditions. The results obtained by the present finite element were compared to those obtained by the analytical solution (Thangaratnam et al. 1989) and a first order shear deformation element (Singha et al. 2001).

Table 4 shows critical buckling temperature of laminated plates made of T300/5208 and AS4/3501-6, respectively. Two type of stacking sequence ([(±Θ°)2]s, [+Θ°2/−Θ°2]s) under various boundary conditions and orientation angles were considered.The obtained results were confronted to results given by Shiau et al. [14] with a finite element based upon the classical plate theory.

From the table 3 and 4, it is shown that the results obtained by the present formulation are in good agreement with those found in the literature.

3.2. Thermal buckling of laminated plates with cut-outs:

In the following, a comparative study is made on the thermal buckling behaviourof cross-ply & angle-ply laminated composite plates with cut-outs. The effect of materials proprieties, cut-outs size, boundary conditions and stacking angle are considered. The plates and the cut-outs are square of shape (a/b=1, a/h=100) as shown in Figure 2. Two stratifications are considered, namely: $[(90/0)_2]_s$ for the cross-ply and $[\pm\theta]_s$ for the angle-ply.

Figure 3 shows the effect of the size of cut-out on the critical buckling temperature of an isotropic plate under clamped (CC), simply-supported (SS), and clamped-simply supported (CS) boundary conditions.The material and geometric properties of the isotropic plate are the same given in table 3. It is seen that, in the case of CC boundary condition, the critical buckling temperature decreases as the cut-out size increases to reach the minimum around e/a=0.2, then starts to increase giving the highest critical buckling temperature at e/a=0.5.

Table 2. Material properties.

Materials	E_1 GPa	E_2 GPa	G_{12} GPa	υ_{12}	α_1 $10^{-6}/C°$	α_2 $10^{-6}/C°$
T300/5208	181	10.3	7.17	0.28	0.02	22.5
AS4/3501-6	142	10.3	7.2	0.27	-0.9	27
E-glass/Epoxy	53.4	17.9	8.6	0.25	6.3	20.5

Table 3. Critical temperature of isotropic square plate (a/h=100, E=2e+11, α=2e^{-6}, υ= 0.3).

Mesh size	4×4	6×6	8×8	12×12
Simply supported				
Analytical (Thangara -tnam et al. 1989)	63.27			
Present element	63.127	63.247	63.262	63.266
FSDT (Singha et al. 2001)	63.198	63.247	63.262	63.266
Clamped				
Analytical (Thangara -tnam et al. 1989)	168.71			
Present element	169.466	168.137	167.892	167.796
FSDT (Singha et al. 2001)	166.517	167.579	167.675	167.856

Table 4. Thermal buckling of rectangular angle-ply laminated plates (a/b=2, b/h=150).

	Stacking sequence	Boundary conditions	Θ°	Shiau et al. (2010)	Present element (10×10)[a]
T300/5208	[(±Θ°)2]s	SS	62°	38.38	38.25
		CC	55°	83.81	83.58
	[+Θ°2/−Θ°2]s	SS	59°	31.62	31.13
		CC	54°	65.30	65.13
AS4/3501-6	[(±Θ°)2]s	SS	56°	44.63	44.52
		CC	52°	88.95	88.70
		CS	57°	47.43	47.16
	[+Θ°2/−Θ°2]s	SS	54°	36.29	35.74
		CC	51°	70.92	70.69

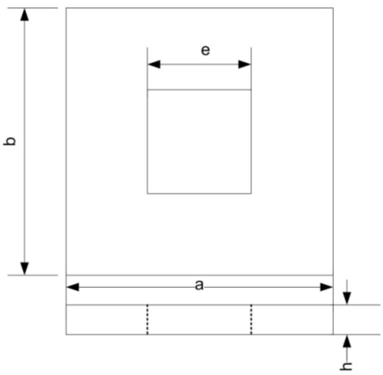


Fig. 2. Geometry of plate with cut-out.

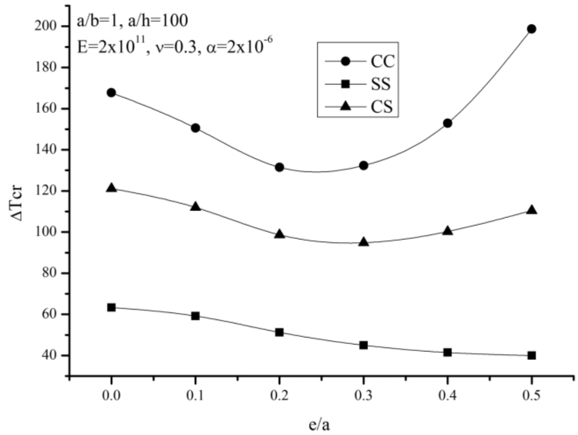
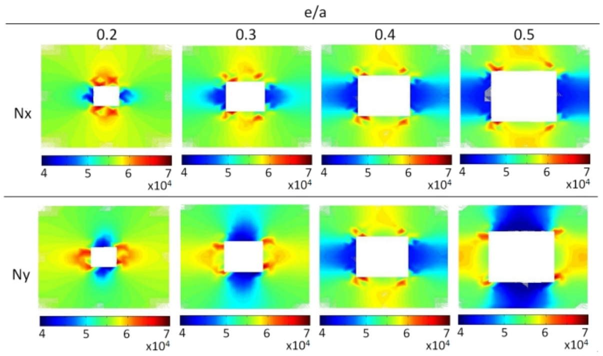
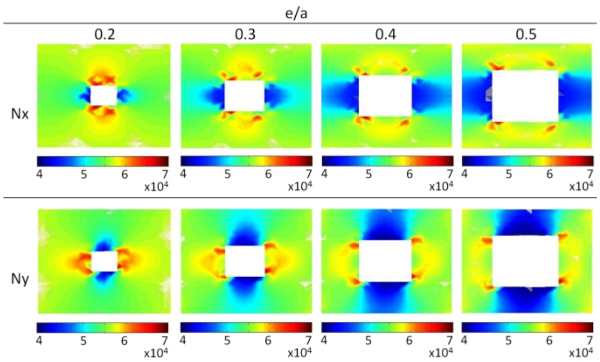


Fig. 3. Critical buckling temperature of isotropic plate vs. cut-outs size for: CC, SS and CS boundary conditions.

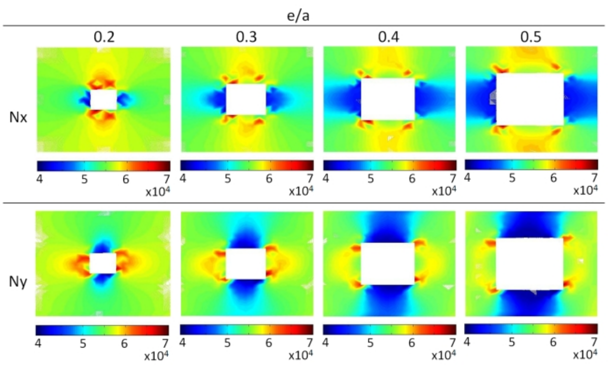
In the case of SS boundary condition, the critical buckling temperature decreases as the cut-out size increases. With the CS boundary condition, as the size of the cut-out increases, the critical buckling temperature decreases to e/a=0.3, then starts to slightly increase with the augmentation of the size of the cut-out. A similar behaviour for the CC and SS boundary conditions in Figure 3 was reported by Ko (1998) and also for the thermal and mechanical buckling of isotropic plates with circular holes (Ko 1998, Lee et al. 1989). The increasing in the critical buckling temperature with the CC and the CS boundary conditions may be caused by the reducing in the stresses concentration in some areas of the plate. According to Lee et al. (1989) a "strong" boundary condition and low concentration of stresses may increase the buckling resistance. In order to support this hypothesis, contour plots of stress resultants distribution (N_x, N_y) versus the cut-out size (e/a = 0.2 - 0.5) are presented in Figures 4 (a, b and c) for the simply supported, clamped and clamped-simply supported boundary conditions, respectively. From the figures 4 (a, b and c),it can be seenthat the stress resultants concentration is decreasing with the increasing in the cut-out size. Also, it can be noticed that the three boundary conditions present the same stress resultants distribution. From these two last remarks, we can say that a combination of a "strong" boundary condition and low concentration of stresses may be the cause of the increasing in the critical buckling temperature in the case of the fully clamped and clamped-simply supported boundary conditions.



(a) Simplysupported isotropic plate



(b) Clamped isotropic plate

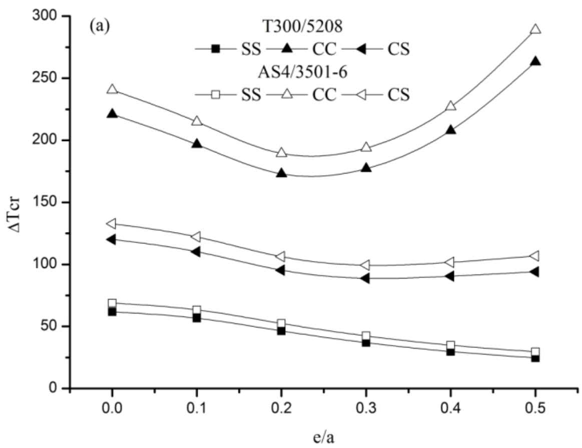


(c) Clamped-simply supported isotropic plate

Fig. 4. Contour plot of Stress resultants vs. cut-out size of a (a) simply supported, (b) clamped and (c) clamped-simply supported isotropic plate.

Figures 5 (a and b) present the effect of the size of the cut-out on the critical buckling temperature of cross-ply laminated plates made of: T300/5208 graphite/epoxy, AS4/3501-6 graphite/epoxy (Fig.5a) and the E-glass/epoxy (Fig.5b). Three types of boundary conditions are considered: CC, SS and CS.

From Figures 5 (a and b), the same behaviour as the isotropic case is observed. It should be noted that similar behaviours were reported for the thermal and mechanical buckling of composite plates with circular holes (Akbulut and Sayman 2001, Avci et al. 2005a, Chen et al. 1991, Noor et al. 1994). We believe that the buckling phenomenon in general is affected much more by the geometry of the plate and the applied boundary conditions, which may explain this similitude.



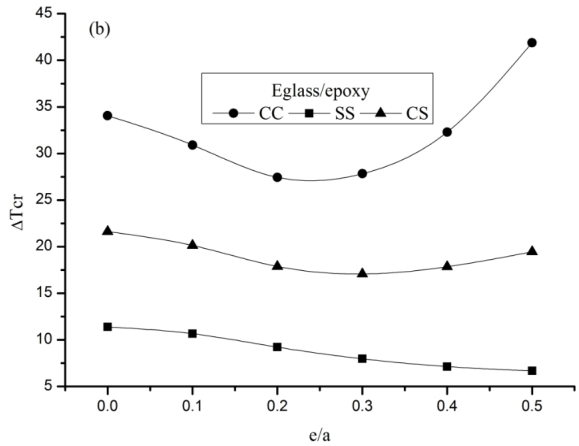
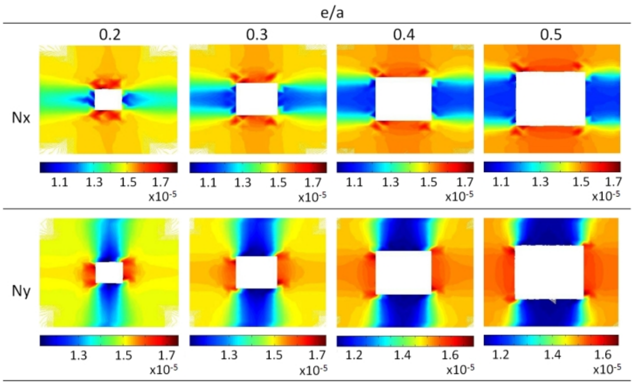


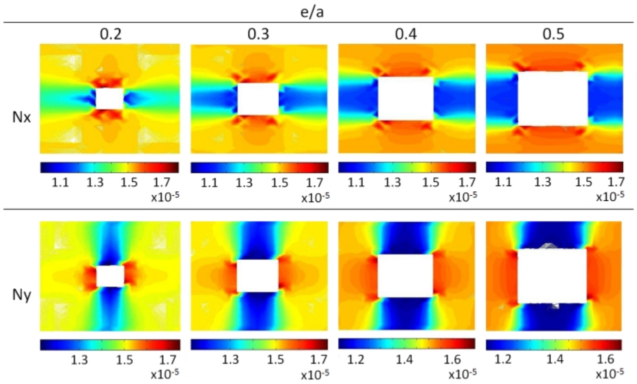
Fig. 5. Critical buckling temperature of cross-ply laminated composite plates vs. cut-outs size for: SS, CC and CS boundary conditions: (a) T300/5208 and AS4/3501-6, (b) E-glass/epoxy.

As aforementioned, a "strong" boundary condition and low concentration of stresses may increase the buckling resistance. The Figures 6 (a, b and c) gather the contour plots of stress resultants distribution (N_x, N_y) for T300/5208 laminated composite plate against the cut-out size for SS, CC, CS boundary conditions, respectively. It can be seen from the figures that as the size of the cut-out increase, the stress resultants concentration decreases. Unlike the isotropic case, the reducing in the stress resultants concentration is more manifested, this may be due to the high rigidity of the laminated composite plate.

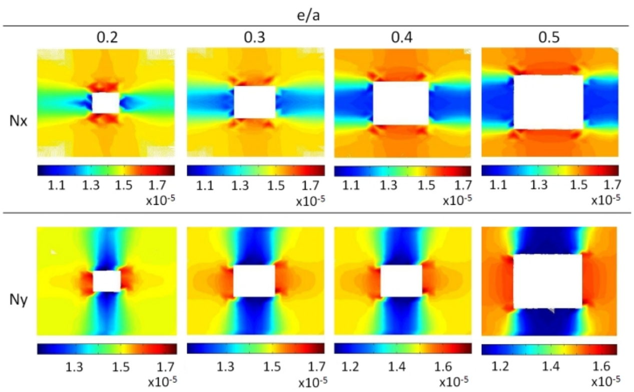
For all boundary conditions, we can see that the E-glass/epoxy (fig.5b) provides lower critical buckling temperatures than those given by the T300/5208 (fig.5a) and the AS4/3501-6 (fig.5a).



(a) Simply supported T300/5208 laminated plate



(b) Clamped T300/5208 laminated plate



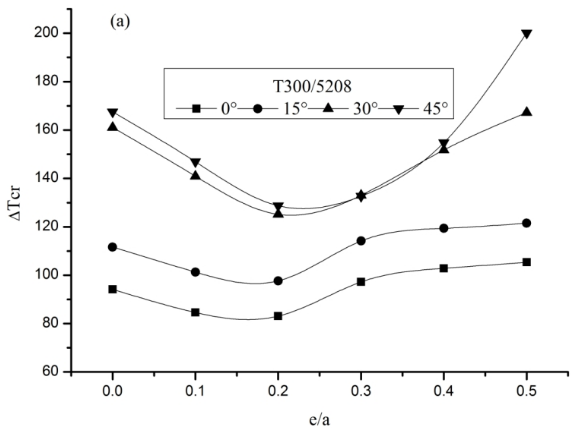
(c) Clamped-simply supported T300/5208 laminated plate

Fig. 6. Contour plot of Stress resultants vs. cut-out size of a (a) simply supported, (b) clampedand (c) clamped-simply supported T300/5208 laminated plate.

From Figure 5a, it can be seen that the critical buckling temperatures given by the T300/5208 and the AS4/3501-6 are very close and the highest are provided by the AS4/3501-6. This can be explained by longitudinal thermal expansion coefficient value α_1=-0.9(10^{-6}/°C)of theAS4/3501-6. According to Shiau et al. (2010) whenthe AS4/3501-6 laminate is subjected to temperature rise, a tension force is generated by the negative coefficient of thermal expansion and it makes the plate exhausts the load-carrying capacity relatively slowly.

Figures 7a and 7b show the effect of the size of the cut-outs on the critical buckling temperature of angle-ply laminated plates under fully clamped (CC) boundary condition. Two materials are taken into account; the T300/5208 graphite/epoxy (fig.7a) and the E-glass/epoxy (fig.7b). Because of the symmetry, only four orientation angles are considered. For both materials and all the considered orientation angles, It is observed that the critical buckling temperature decreases with the increasing of the size of the cut-outs, to about e/a=0.2, then starts to increase with the increasing of the size of the cut-outs.

In the case of the T300/5208 (fig.7a), we notice that with the 45°, the decreasing and the increasing in the critical buckling temperature are more manifested compared to the other orientations especially the 0° and the 15°. In these later cases, we can see that the critical buckling temperatures are slightly affected by the change in the size of the cut-out. In the case of



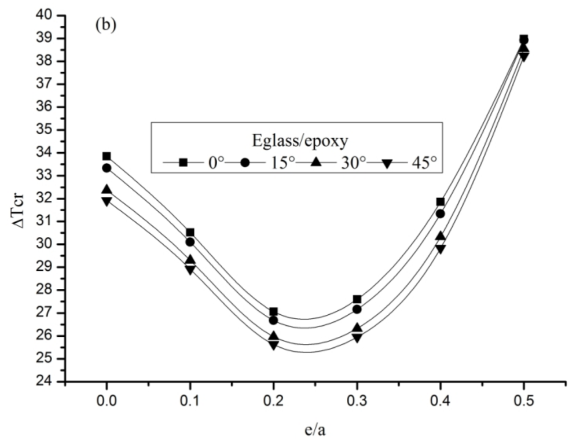


Fig. 7. Critical buckling temperature of clamped (CC) angle-ply laminated composite plate vs. cut-outs size: (a) T300/5208, (b) E-glass/epoxy.

the E-glass/epoxy (fig.7b), the critical buckling temperatures are quite close; the effect of the stacking angle variations is less pronounced compared to the T300/5208. This is probably due to the low modulus E_1/E_2 ratio and thermal expansion α_2/α_1 ratio of the E-glass-epoxy.

The effect of the size of the cut-outs on the critical buckling temperature of simply supported (SS) T300/5206 and E-glass/epoxy composite laminated plates is presented in Figures 8a and 8b, respectively.

For both materials and all the considered stacking angles, it can be observed that the critical buckling temperature decreases with the increasing of the size of the cut-out, except for the T300/5208 (fig.8a) with 0° and 15°, where we notice a slight augmentation with e/a=0.1.

Figure 9 (a and b) show the effect of the size of the cut-out on the critical buckling temperature of clamped-simply supported (CS) boundary condition of angle-ply T300/5208 and E-glass/epoxy composite laminated plates, respectively. In the case of the T300/5208 (fig.9a), it is seen that when the fibres are in direction of the clamped edges, especially with 0° and 15°, we notice a similar behaviour of a fully clamped plate. When the fibres direction approach the simply supported edges (75°and 90°), the critical buckling temperatures decrease with the increasing of e/a ratio

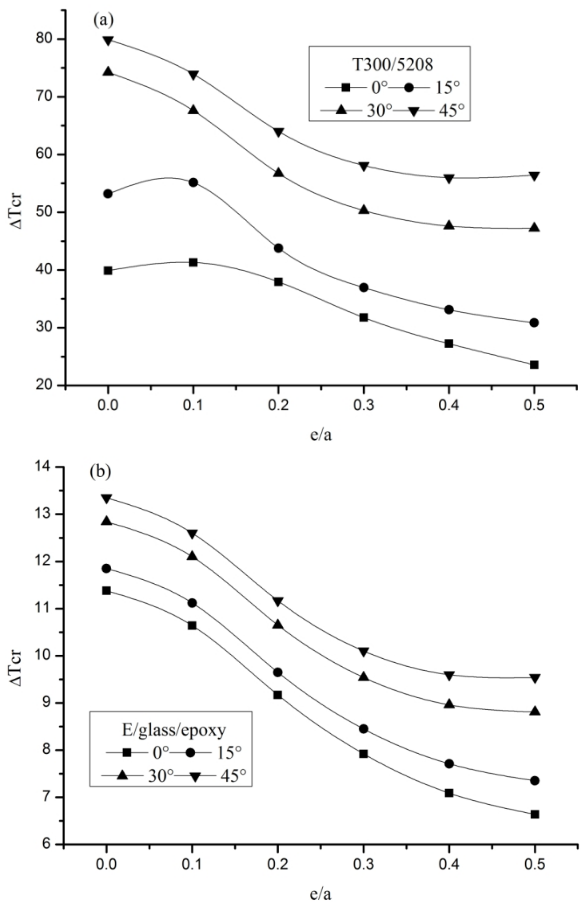


Fig. 8. Critical buckling temperature of simply supported (SS) angle-ply laminated composite plate vs. cut-outs size : (a) T300/5208, (b) E-glass/epoxy.

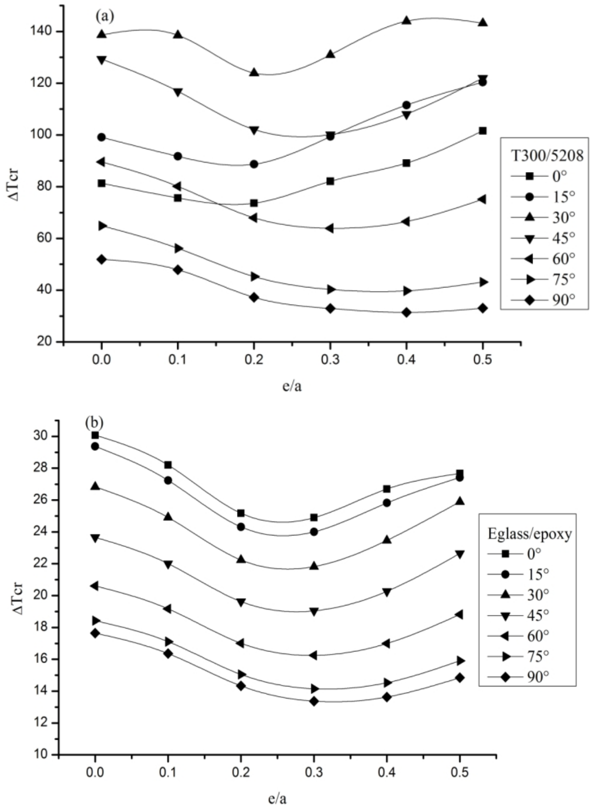


Fig. 9. Critical buckling temperature of clamped-simply supported (CS) angle-ply laminated composite plate vs. cut-outs size: (a) T300/5208, (b) E-glass/epoxy.

In Figure 9b, it's well observed that for all the orientation angles, the critical buckling temperatures of the E-glass/epoxy decrease as the size of the cut-outs increase to about e/a=0.3, then start to increase with the increasing of e/a ratio.

5. Conclusion

In this paper, the thermal buckling behaviour of laminated composite plates with cut-outs under uniform temperature distribution using the finite element method is presented.

A finite element previously extended by the authors to study the thermal buckling behaviour of laminated plates is used (Ounis et al. 2014). The finite element is a combination of a linear isoparametric membrane element and a high precision rectangular Hermitian element. The parametric study showed that the boundary conditions and size of the cut-outs significantly affect the critical buckling temperatures of laminated composite plates for the three considered materials; the T300/5208 Graphite/Epoxy, the AS4/3501-6 Graphite/Epoxy and the E-glass/Epoxy, and for both stratifications the cross-ply and angle ply. It was concluded that in the case of clamped (CC), the presence of cut-outs of a size beyond the e/a = 0.2 increases the resistance to buckling, while with the simply supported (SS) boundary condition, the critical temperatures decrease with the increasing of the cut-outs size. It was also concluded that the increasing in the size of the cut-out reduce the stress resultants concentration in some area of the plate. Combined with a "strong" boundary condition, this reduction provokes an increasing in the critical buckling temperature of the plate, as the case of CC and CS boundary condition. The study also showed that the E1/ E2 and α2/α1 ratios play an important role in the determination of the critical buckling temperature.

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