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Numerical modeling of defective hybrid composite plates

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ABSTRACT

It is known that the optimization of the positioning of reinforcements within a composite material is likely to increase significantly the performance of a structure. Accordingly, buckling is the most critical failure mode for notched and non-stiffened plates under axial compressive stress. In this study, the buckling response of laminated plates made of hybrid composite materials with and without elliptical notches is analyzed using finite element methods. The plates are made of carbon/epoxy/aluminum and arranged in following ordered manner [Al/ (θ/-θ) /Al]. The resistance to buckling of the hybrid plates under uniaxial compression is examined according to fiber orientations, the orientation of the notch and finally the thickness of the aluminum layer in the composite material. The results showed that when the fibers are at $\theta = 90^0$ the amplification of the critical load of buckling in the hybrid notchless plate is of the order of 59% and 27.66% for a thickness of the aluminum layer t_{Al}= 0.2mm and 0.127mm respectively. The elliptical notch oriented at 0° reduces the maximum load four times more than when oriented at 90^o.

1. Introduction

The use of materials having specific mechanical properties permits the sizing of lighter structures but equally even more efficient than the conventional ones. The composite materials in form of laminated plates or shells have found a growing use in many industrial applications. Moreover, composite materials reinforced with carbon fiber are now used more and more in many areas such as aeronautics, astronautics, pressurized vessels, pipes, ships and sports equipment due to their high resistance to fatigue and corrosion, therefore, a satisfactory durability. In addition, the minimization of the structural mass in the aeronautical industry leads directly to reducing the aircraft fuel consumption which constitutes an important technological challenge.

The assessment of appropriate levels of security is required by the process of modern design. Particular attention is paid to the behavior to buckling which must be understood and predicted in order to determine effective models and the safe loading conditions. In industry, the laminated composites have proven to be very efficient in the fabrication of parts of primary structures, due to their performance, quality of lightness and form flexibility (Kweon et al., 2006). The design of this type of structures needs tools to model their sophisticated mechanical behavior, taking into account the specificities of these materials. The numerical methods and in particular the finite element methods are essential for sizing these complex composite structures. Currently, the analysis of the behavior of laminated plates always remains an open research problem, due to their complex behavior (Komur et al., 2010).

Several studies of stability of laminated plates have been concentrated on the rectangular plates (Rhodes et al., 1984; Nemeth, 1988; Mroz, 2011; Reddy and Harish, 2014). It is known that the resistance to buckling of rectangular plates depends on the boundary conditions and the orientations of the folds (Hu and Lin, 1995). The thin walled composite structures which are widely used become unstable when they are subjected to mechanical or thermal loads leading to buckling. Accordingly, their behaviors in buckling are significant factors in safe and reliable design (Baba, 2007). Baba and Baltaci (2007) have performed a buckling analysis of a laminated composite rectangular plate having a circular hole at the center. Hamani et al. (2012) have studied the effect of fiber orientation on the critical load of buckling of symmetrical laminated composite

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plates having a crack emanating from a circular notch. They indicated that the critical load of buckling reaches its maximum values when the fibers are oriented in an interval varying from 50° to 90°. Ouinas and Achour (2013) have studied the effect of the presence of an elliptical notch on the buckling of laminated boron/ epoxy plates arranged anti-symmetrically [(θ/ -θ)].

In this study the buckling of composite plates made of hybrid carbon/epoxy/ aluminum material with and without elliptical notches is analyzed using finite element code ABAQUS 6.11. The effects of the notch orientation with respect to x-axis, the orientation of plies and the thickness of the ply on the buckling load have been examined. Moreover, the effect of the thickness of the layer of aluminum has also been considered.

2. Finite element model

In this study, a thin square plate, 100mm x 100mm x 1.162mm, made of hybrid carbon/epoxy/ aluminum composite material is analyzed. The lower edge of the plate is fixed and the displacement on the upper edge is assumed to be free along the y-axis. The plate is subjected to a uniaxial compression in the vertical direction under the load per unit length $\sigma = 1N/mm$. The plate is numerically modeled using the finite element code ABAQUS 6.11. The finite element mesh involved a total of 33328 S8R quadrilateral and 397 STRI65 elements with a refined mesh at the vicinity of the notch as shown in Fig. 1 and Fig. 2.

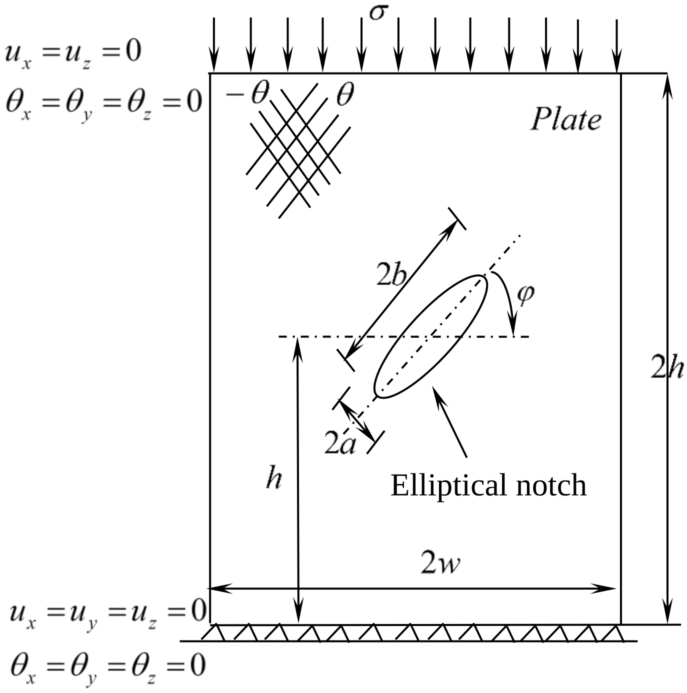


Fig. 1: Geometric model of the plate in the presence of an elliptical notch

The plate is composed of eight plies, six of carbon/epoxy and two of aluminum alloy. The thickness of the carbon/epoxy layer is 0.127 mm and the fibers are symmetrically crossed in an orderly alternate manner according to an angle θ and $-\theta$ respectively (Fig. 3). The layers of the aluminum are outside of the plate and each has a thickness of 0.2mm.

As shown in Fig. 3, several mesh sizes are used in the numerical calculation to examine the accuracy and the convergence of a test case chosen where the ratio of the elliptical notch b/a=3, and the orientation of the layers is [-45/45]3. The classical model theory of laminates is implemented using the shell elements S4R, S8R of the software Abaqus with the composite lay-up option. The linear elements and quadratic with reduced integration S4R and S8R are generally well suited for the calculation of semi-thick or thin shells.

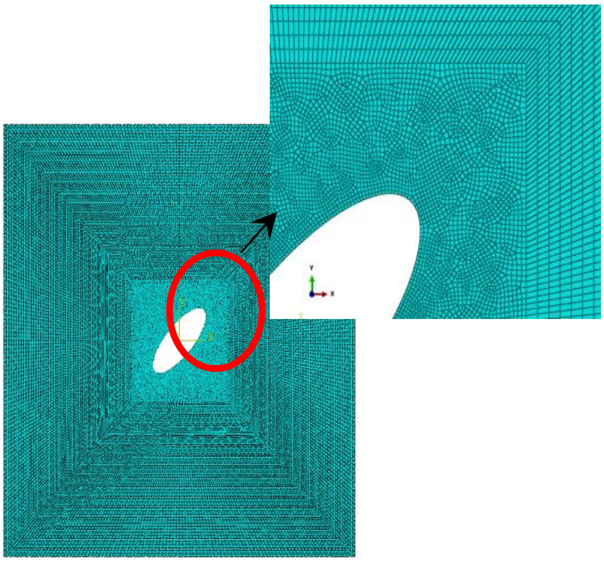


Fig. 2: Meshing of the plate in the presence of an elliptical notch

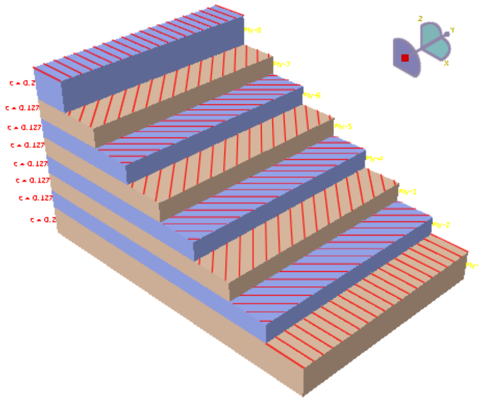


Fig. 3: Fiber orientation in the laminated plate

The buckling parameters calculated by the two types of finite elements shell elements S8R and S8R5 are compared as illustrated in Fig. 4. It is worth noting that the stability of the buckling parameter is marked when the size of the edge element was less than 2 mm, regardless of the type of element used S8R or S8R5. More precision is attained when the size of the element is taken equal to 0.4mm. The mechanical properties of the hybrid composite plate are given in Table 1.

Table 1: Mechanical properties of the hybrid composite plate

Properties	Aluminum 2024T3	Carbone/époxy
$E_1(MPa)$	72.4	145
$E_2(MPa)$	-	10
υ_{12}	0.33	0.25
υ_{23}	-	0.25
$G_{12}(MPa)$	27	7
$G_{13}(MPa)$	-	7
$G_{23}(MPa)$	-	3.7

In real applications, notches in composite plates could be of different forms according to the design needs. The shape of the notch has been assumed primarily to be an elliptical hole at the centre of the plate.

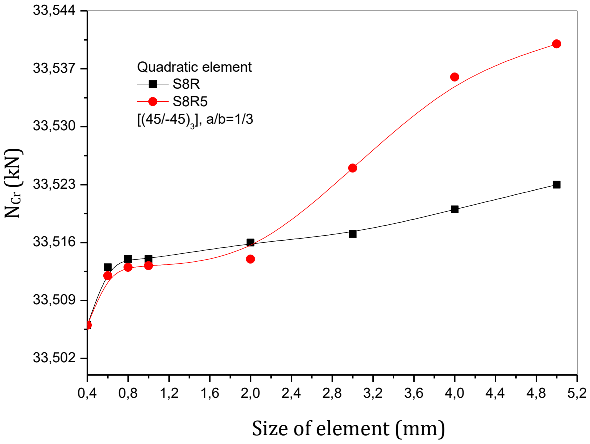


Fig. 4: Effect of the element size on the convergence of NCR

However, the effect of different positions for the elliptical notch on the buckling load is considered. These positions are represented by an angle between the major axis of the notch which is the x-axis by 0°, 15, 30, 45, 60, 75, and 90° as shown in Fig. 1. The dimensions of the main diameters of the ellipse are represented by a and b respectively. The ratio of the two geometric parameters of the elliptical notch is kept constant (a/b=1/3). The effect of the circular notch is also analyzed as a special case when a=b. In addition, particular attention has been paid to the number of alternate cross over plies of the laminated plate as well as the ply orientations.

3. Results and discussion

3. 1. Effect of the ply orientations in the presence of two different aluminum layers

Fig. 5 shows the variation of the buckling critical load versus the angle of orientation of the plies where the presence of the aluminum layers is highlight. Two configurations have been analyzed; a carbon/epoxy composite plate and a hybrid composite one, having an outside aluminum layer 0.2 mm thick. Six composite layers are oriented at θ and $-\theta$ without a geometric defect. The evolution of the critical load in first mode of buckling of the composite laminated plate as a function of the angle of the plies is clearly highlighted. It can be noticed that the buckling critical load remains quasi-constant in the range 0° to 30°. Beyond this declination, the load is increased to an asymptotic maximum value corresponding to the angle $\theta = 90^0$ The buckling critical load in the hybrid plate having an aluminum thickness layer t_{Al} = 0.2mm is found to be more important than of the carbon/epoxy one. The amplification of N has been of the order of 59% when the fibers are at $\theta = 90^0$. For the hybrid plate having t_{Al} =0.127mm, the amplification factor has reached 27.66 % which indicates that the buckling loads are sensitive when the ply angle is higher than 30°.

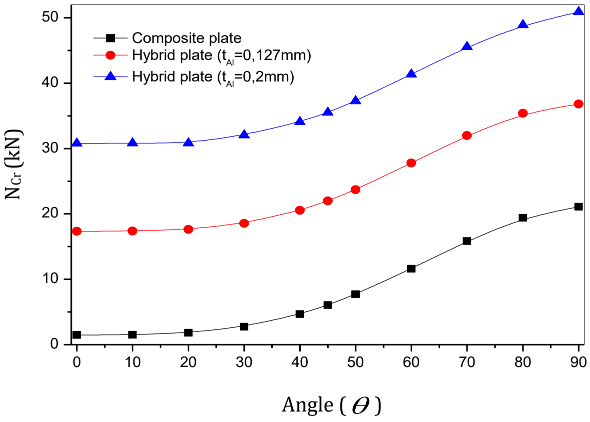
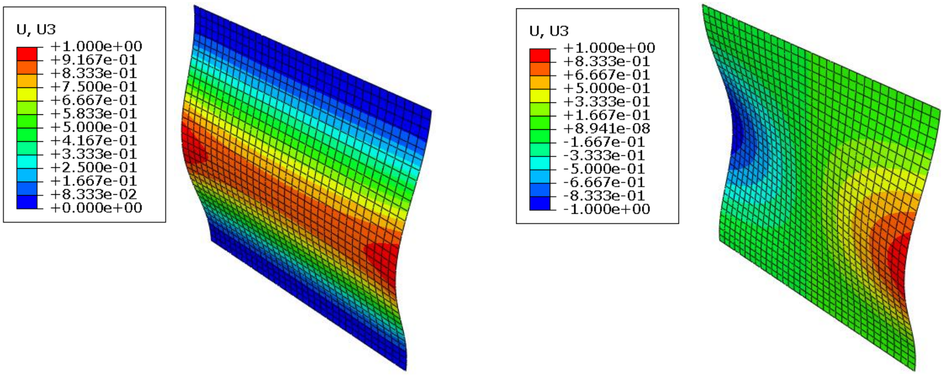


Fig. 5: Effect of the aluminum layer on the buckling critical load

The design of a laminated composite is based on the optimization, therefore the best fiber orientation of each layer should be found. Fig. 6 illustrates 10 buckling modes of a hybrid composite plate when the plies are oriented at 90°. It is clear that the buckling critical load increases with the buckling mode for the same ply orientations.

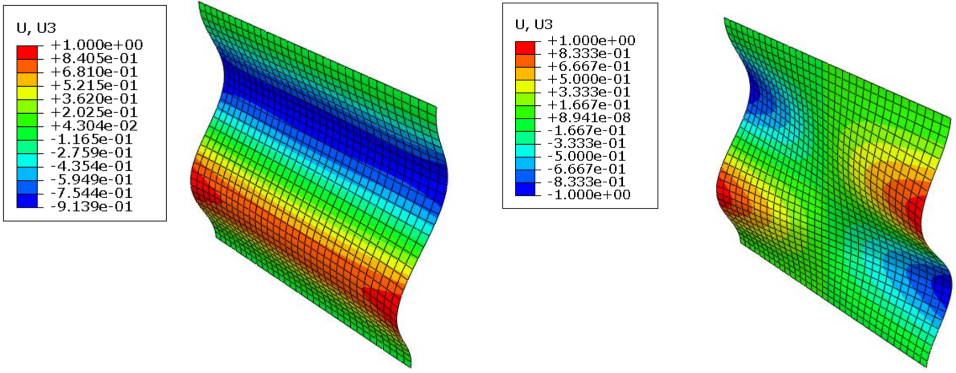
3.2. Influence of the ply orientation for different declinations on the buckling load

Fig. 7 illustrates the influence of the angle of fiber orientation on the variation of the buckling load of a hybrid composite plate containing an elliptical notch whose major axes ratio is a/b=1/3. Thus, the variation of the declination angle of the elliptical notch with regard to the x-axis is highlighted. It is clear that the critical buckling load increases according to three stages as a function of the fiber angle of declination of the composite material. In the first stage, where $0^0 \leq \theta \leq 30^0$, the critical load has been found almost stable. However, in the second stage where $30^0 \leq \theta \leq 70^0$, the critical buckling is found to increase quadratic ally. Finally, in the last stage, where $\theta \geq 70^0$, the increase is found to be less sensitive. The lowest values of the buckling critical load are obtained when the fibers are oriented perpendicular to the applied load $\theta = 0^0$ while the maximum values are obtained when the fibers are parallel to the applied load $\theta = 90^0$. The differences between their trends are quasi-constant. It is very clear that the buckling load of the plate is strongly affected by the stacking order of the composite laminates. Therefore, for the laminated plate to resist better to the buckling load, the greatest ply orientations should be oriented with regards to the x-axis. In addition, the effect of the orientation of the elliptical notch has been considered as well. It is to be noted, that in this case, the increase of the angle of declination of the notch with regards to the x axis lead to an increase in the difference between the buckling loads, and sensitive when the ply orientation is greater than 45^0 ($\theta > 45^0$).



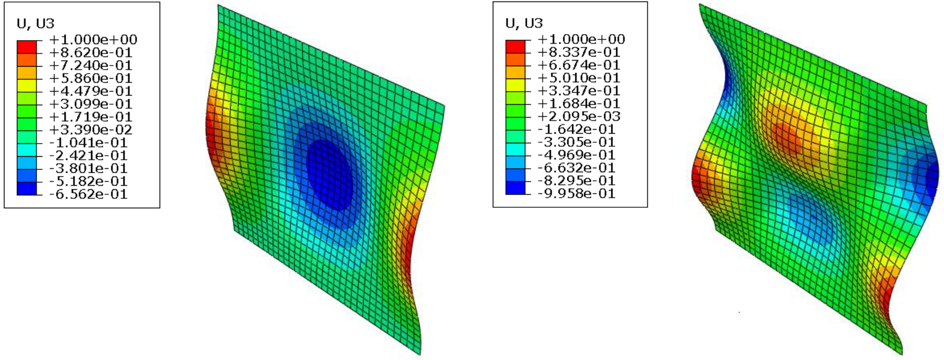
(a) Mode 1: N_{cr} = 100 N/mm

(b) Mode 2: N_{cr} = 128.28N/mm



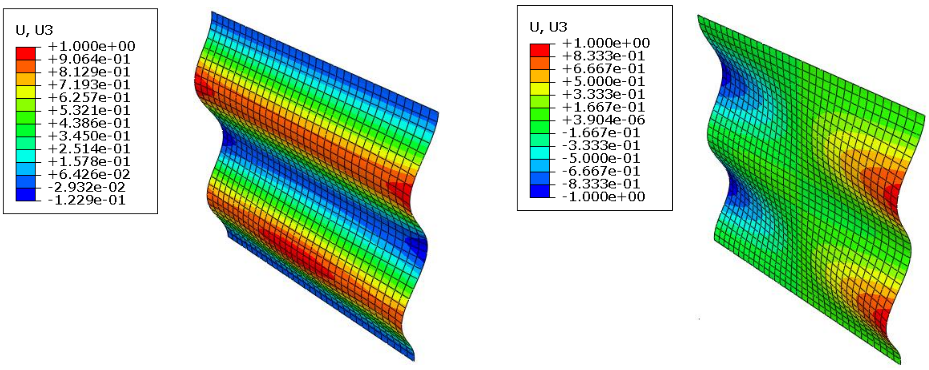
(c) Mode 3: N_{cr} = 203,08 N/mm

(d) Mode 4: N_{cr} = 232,44 N/mm



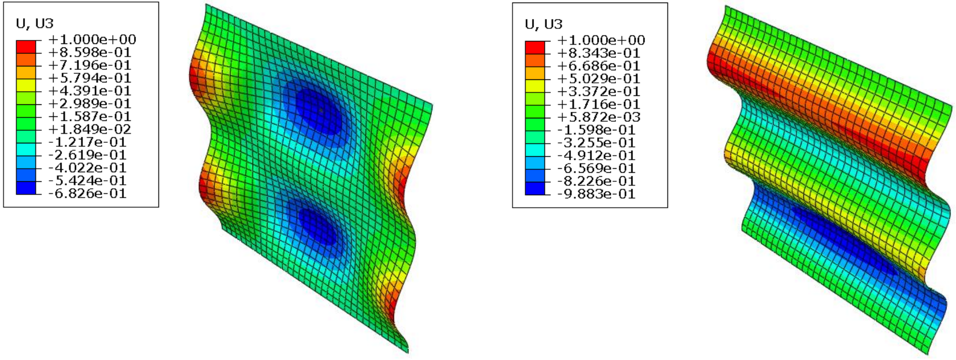
(e) Mode 5: N_{cr}= 176,6 N/mm

(f) Mode 6: N_{cr} = 336,681 N/mm



(g) Mode 7: N_{cr} = 393,02 N/mm

(h) Mode 8: N_{cr} = 422,22 N/mm



(i) Mode 9: N_{cr} = 520,93 N/mm

(j) Mode 10: N_{cr} = 584,75 N/mm

Fig. 6: Different buckling modes of a hybrid composite notchless panel (case $\theta = 90^0$)

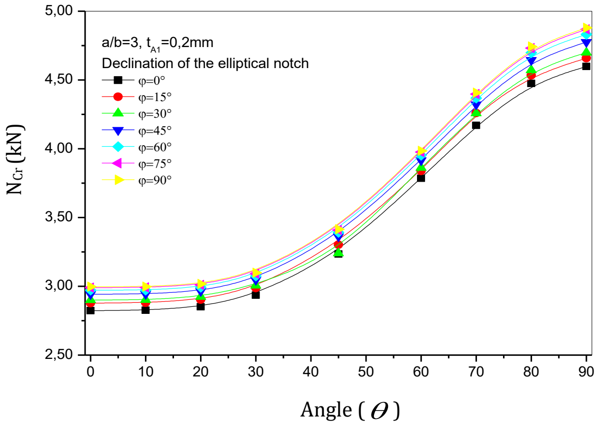


Fig. 7: Effect of fiber orientation on the buckling load variation

For a better illustration of this effect, the variation of a dimensionless reduction factor of the buckling load is shown in Fig. 8 as a function of the declination angle (θ). The reduction factor is defined by (Eq. 1):

$$N^* = 1 - \frac{N_{wn}}{N_{wtn}} \tag{1}$$

where, N_{wn} and N_{wtn} are the buckling loads for the hybrid plate with and without the elliptical notch respectively.

From Fig. 8, the critical stress was found to be reduced by 2.8% when the elliptical notch was oriented at 90° and then moved to 8.5% for an orientation of 0°. The maximum reduction was obtained for an orientation of the fibers at 45°and this regardless of the orientation of the elliptical notch with respect to the applied load.

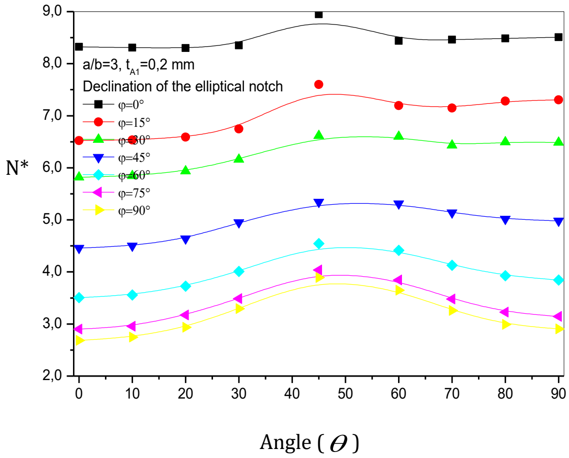


Fig. 8: Effect of fibre orientation on the buckling load variation

3.3. Influence of the aluminum layer thickness

To examine the thickness effect of the aluminum layer and the position of the elliptical notch on the evolution of the critical load of the hybrid plate, three cases are considered. For the first case, the notch major axis is taken parallel to the x-axis; the second case, the notch minor axis is perpendicular to the y-direction and the third case, the notch major axis has a 45° declination with respect to the x-axis. The orientations of the composite plies were [Al/(0)$_6$/Al], [Al/(45/-45)$_3$/Al] and [Al/(90)$_6$/Al]. The results obtained are represented in Fig. 9.

It is clear that the critical buckling load increases exponentially with the increase of the thickness of the aluminum layer and this regardless of the orientation of the plies and the orientation of the elliptical notch. The increase of the aluminum layer from 0.127 mm to 0.8 mm increased the buckling critical load by 94.62%, 93.36% and 89.44% respectively for the [Al/ (0)₆ /Al], [Al/ (45/-45)₃ /Al] and [Al/ (90)₆/ Al] plies when the notch orientation $\varphi = 0^0$ Regarding the two other orientations, the increase is of the order of 94,624 %, 93,395% and 89.4% for $\varphi = 45^0$ and 94,645 %, 93,435% and 90.026% for $\varphi = 90^0$. It is worth noting that the effect of the notch declination on the critical load when the aluminum layer became important is not significant.

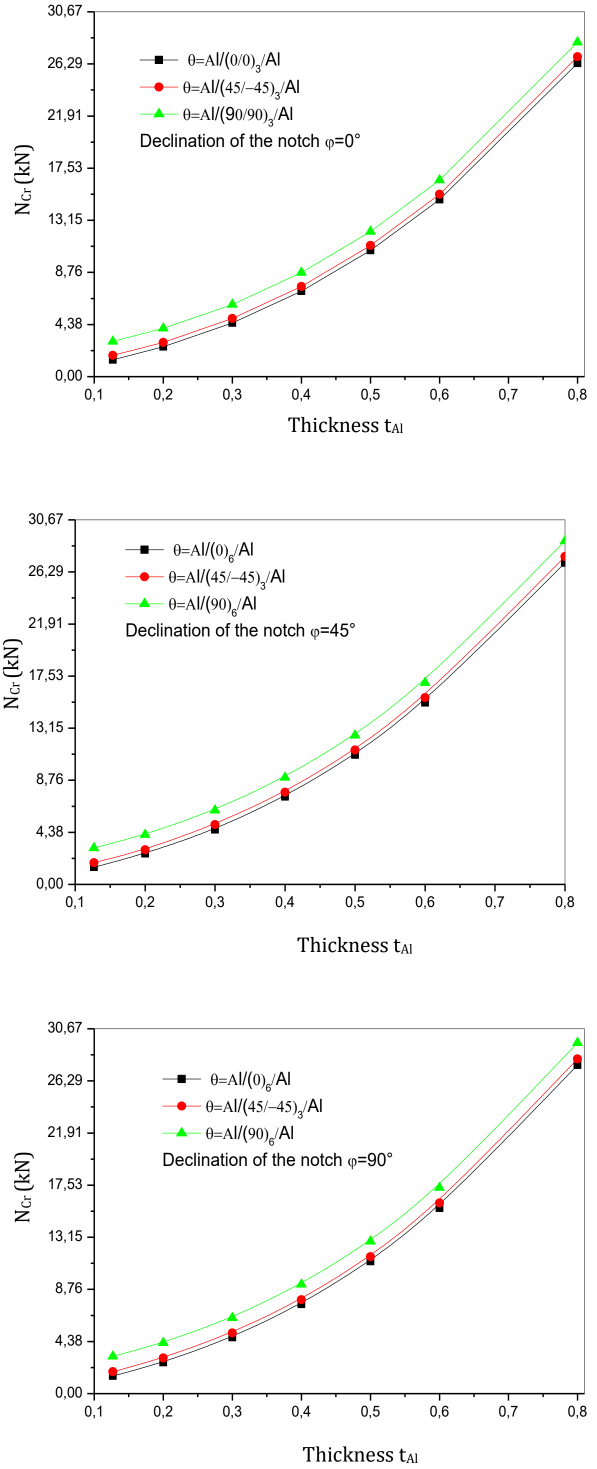


Fig. 9: Effect of the aluminum layer thickness on the critical load

Fig. 10 shows the thickness effect of the aluminum layer on the critical load amplification for the three previous cases. To illustrate this, the variation of a dimensionless reduction factor N^* of the buckling load as a function of the thickness of the aluminum layer is drawn.

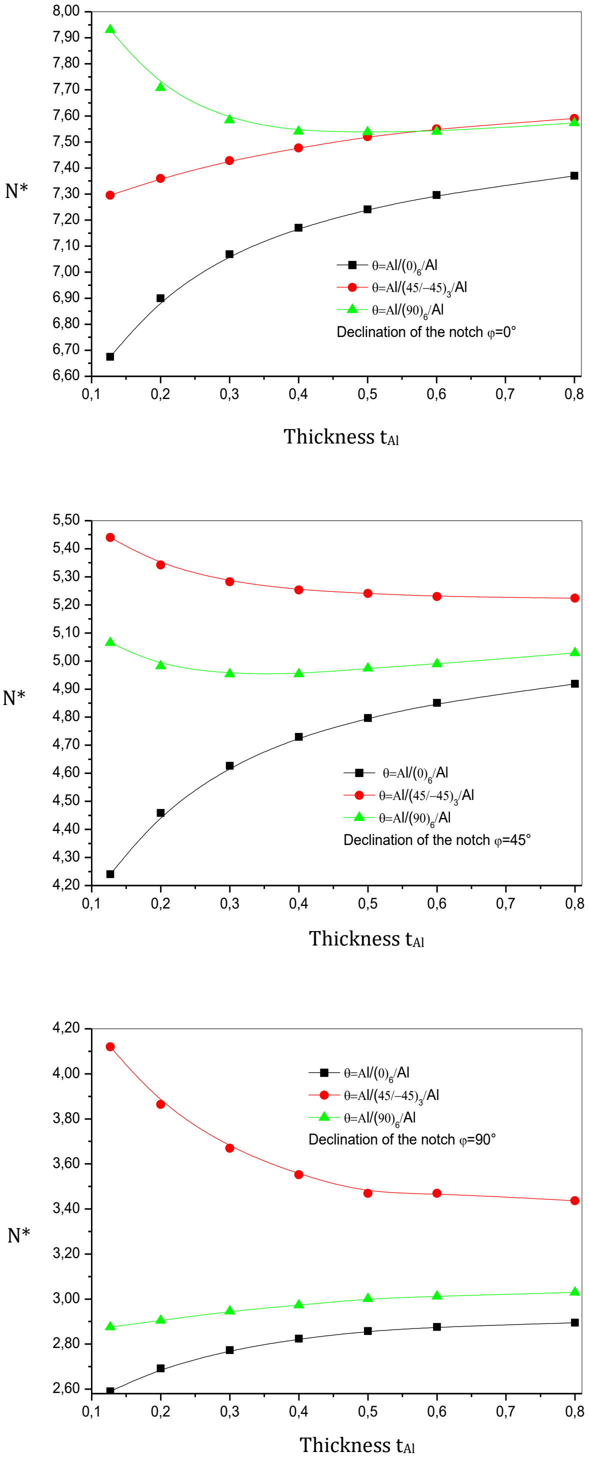


Fig. 10: Effect of the aluminum layer thickness on the buckling load amplification

For the orientations of the plies at 0° and 45°, the reduction factor increased quadratically with the increase of the thickness of the aluminum layer up to 0.8mm. It reached respectively 7.4% and 7.6% in the presence of a notch oriented at 0^0. An inverse behavior has been observed when the plies are at 90^0; the factor N^* increased exponentially with the decrease of the aluminum layer. The maximum value was attained for the smallest thickness which was of the order of about 8 %. When the elliptical notch was declined at 45^0, the factor N^* decrease from 5.44% and 5.07% for t_{Al}=0.127mm down to 5.22 % and 5.03% for t_{Al}=0.8mm for both orientations $\theta = 45^0$ and $\theta = 90^0$.

The lowest reductions are obtained for $\theta = 90^0$. For this last case, the maximum reduction is 4.92% for t_{Al}=0.8mm. Comparing the last case ($\varphi = 90^0$) and the first case ($\varphi = 0^0$), the reduction factor N^* is found to be roughly halved for both the extreme thicknesses (t_{Al} = 0.127mm and t_{Al} = 0.8mm) and for the different ply orientations $\varphi = 0^0$, $\varphi = 45^0$ and $\varphi = 90^0$.

4. Conclusion

In this study the buckling response of a hybrid composite square plate in the presence of an elliptical notch is investigated. The effects of, the orientation angle of the elliptical notch, the notch geometry, the orientation of the plies of the composite material and the thickness of the aluminum layer on the variation of the buckling load are examined leading to the following findings:

- The critical buckling load amplification in the notchless hybrid plate is of the order of 59% and 27.66% respectively for the thickness of the aluminum layer t_{Al}= 0.2mm and 0.127mm, when the fibers are oriented at $\theta = 90^0$.
- The buckling load increases exponentially with regard to the increase of the orientation angle of the composite material fibers. This increase is much faster and more important for angles $\theta \geq 45^0$.
- For an aluminum layer of 0.2mm in the hybrid plate, the critical stress is reduced by 2.8% and 8.5% when the angles of declination of the elliptical notch are respectively 90^0 and 0^0. The maximum reduction is obtained for an orientation of the fibers at 45^0 and this regardless of the orientation of the elliptical notch with respect to the applied load.
- The elliptical notch declined at 0°, reduces the maximum load four times more than when declined at 90^0.

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