The influence of fibre orientation and of the adjacent layers on the delamination of laminated composites

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Abstract. The paper presents a comparative analysis between different configurations of composite laminates with respect to the delamination onset and growth. The results are presented in terms of the total displacement jumps at the crack tip for an initial imposed displacement up to the final delamination. Therefore, the influence of fibre orientation and the suitable selection of the configuration of the composite laminates are discussed. Moreover, the effect of the adjacent layers on the interlaminar damage of composite laminates is analysed. In this context, a significant number of numerical models have been carried out for two different configurations of multi-layered composites, namely [0°/+θ/+θ/0°] and [0°/+θ/-θ/0°]. The influence of the orientation of the adjacent layers is investigated, as well as the sign of the fibre orientation angles. The analysed composite laminates are subjected to tensile opening fracture mode, considering a pre-existing initial crack located at the interface between the layers from the middle plane. The variation of the mode I opening displacement with respect to the fibre orientation angle of the adjacent layers is graphically illustrated. The obtained results show similarities in the variation of Poisson’s ratio with respect to the fibre orientation. Therefore, the mismatch of the Poisson’s ratio of the adjacent laminas may involve significant interlaminar stresses which can lead to a delamination failure or an opening fracture mode.

1. Introduction

Fibre reinforced polymeric (FRP) composites are widely used in engineering applications due to their outstanding advantages, such as high specific strength and specific stiffness, as well as good corrosion resistance. Multi-layered composites are formed by stacking two or more laminas, with different fibre orientation angles, enabling the response to complex states of stresses [1-3]. Various failure modes may occur on composite laminates, which can lead to significant stiffness and strength reduction or to the complete loss of load carrying capacity [4]. The delamination onset caused by the interlaminar stresses or manufacturing defects can lead to serious problems, such as premature buckling, moisture infiltration, stiffness degradation or delamination growth and separation of the laminate layers.

 Nowadays, a growing interest is directed towards the analysis of the delamination failure and several approaches for the simulation of the delamination onset and growth can be found in the literature [5-9]. The interface between two consecutive fibre reinforced composite laminas is critical for the damage onset and the delamination evolution between adjacent layers.

In this paper, delamination is investigated in the context of the influence of the fibre orientation angles and of the effect of the adjacent layers on the interlaminar damage growth.
2. Description of the numerical modelling of delamination growth

Two different types of specially orthotropic composite laminates are first analysed: a cross-ply laminate \([90/0/90_{2}/0_{2}]S\) and an angle-ply laminate \([\pm 60_{3}]S\), as shown in figures 1 and 2. The numerical modelling of the delamination growth of the laminated composites is performed in ANSYS Workbench and ANSYS Composite Prep/Post [10].

The effect of adjacent layers on the interlaminar damage of composite laminates is also analysed. A significant number of numerical models have been carried out for two different configurations of multi-layered composites, such as \([0_5/+\theta/+\theta/0_5]\) and \([0_5/+\theta/-\theta/0_5]\). The effect of the orientation of the adjacent layers is investigated, as well as the influence of the sign of the fibre orientation angles.

A comprehensive understanding of the composite delamination is developed from the fundamental principles of fracture mechanics and their extended version from the isotropic materials to the anisotropic materials, such as composite laminates.

Three interlaminar fracture modes may occur, which are characterized by a separation or a shear of the cohesive zone involving the adjacent plies. In this paper, a *Mode I* delamination failure is analysed, known as an *opening* fracture mode. The *Mode I* delamination failure is defined as a normal separation of two adjacent layers of the composite laminate, which may lead to an interlaminar crack extension.

Two different approaches are generally used to characterize and analyse the delamination onset and delamination growth: *The Virtual Crack Closure Technique (VCCT)* and *The Cohesive Zone Method (CZM)* [11,12].

*The VCCT* is a method based on the energy criterion and on the linear-elastic fracture mechanics theory. Generally, this technique provides two alternative methods, such as: *the energy release rate* and *the stress intensity factor* [11].

*The CZM* is represented by the constitutive relation expressed by the forces of traction separation which act on the interface of two adjacent layers and the corresponding opening displacement jump, initiated by a gradual failure of the cohesive zone [13].

In this paper, the numerical modelling for the analysed configurations of composite laminates is realized for a *Mode I* fracture type, using the *CZM* approach. The geometry description for the *opening* interlaminar fracture mode is shown in figure 3. The dimensions and the significance of the characteristic elements are: \(L = 85\) mm, \(b = 25\) mm – the length and the width of the composite laminate; \(2H\) is the total thickness of the element; \(P\) or \(\Delta\) represents the tensile load or the imposed displacement, respectively, which acts normal to each side of the free edges of exterior laminas; \(\delta\) – the total opening displacement jump; \(a = 10\) mm is the initial crack length.
The constitutive relation used in this numerical analysis for the CZM is the exponential traction-separation law, which leads to the finest results and takes into consideration the nonlinear behaviour of the laminated composites delamination. Figure 4 shows the variation of the reactive force with respect to the opening displacement jump. Therefore, the reactive force develops an increase until reaching a maximum, $F_{cr}$, and it is reduced to zero, as the cohesive surfaces separate, resulting in a complete separation of the adjacent layers, $\delta_f$ [13].

![Figure 3. The geometry description for the Mode I interlaminar fracture numerical modelling.](image1)

![Figure 4. The exponential traction-separation curve for cohesive zone model.](image2)

The mechanical properties of the unidirectional composite layers made of S glass fibres embedded in an epoxy resin are shown in table 1.

| Property | Value |
|----------|-------|
| $E_1$ (GPa) | 52.94 |
| $E_2$ (GPa) | 13.93 |
| $G_{12}$ (GPa) | 5.07 |
| $v_{12}$ | 0.292 |
| $f_{1t}$ (MPa) | 2836 |
| $f_{1c}$ (MPa) | 1122 |
| $f_{2t}$ (MPa) | 62.53 |
| $f_{2c}$ (MPa) | 125.1 |
| $f_{12s}$ (MPa) | 58.29 |

*where: $E_1$ and $E_2$ represent the longitudinal and transverse modulus, respectively; $G_{12}$ is the in-plane shear modulus; $v_{12}$ represents the in-plane major Poisson’s ratio; $f_{1t}$ and $f_{1c}$ are the longitudinal tensile strength and the longitudinal compressive strength; $f_{2t}$ and $f_{2c}$ are the transverse tensile strength and the transverse compressive strength, respectively; $f_{12s}$ is the in-plane shear strength.

3. Results and Discussion

3.1. The influence of fibres orientation – a comparative analysis

In order to demonstrate the influence of the fibre orientation angles and of the configurations of multi-layered composites on the delamination onset and delamination growth, two different types of previously discussed laminated composites are analysed: the cross-ply and the angle-ply laminate.

3.1.1. Initial crack tip opening displacements and equivalent stress distributions. After a number of trials, an initial imposed displacement equal to 40mm is selected in order to illustrate the delamination onset on the laminated composites. Figure 5 illustrates the deformed shape of the cross-ply laminate subjected to traction-separation forces in a Mode I fracture type, and the crack tip opening displacement, equal to 47.95 mm. The initial displacement jumps for both configurations analysed are
presented in table 2. The results show that for the same initial imposed displacement, the crack tip opening displacement is higher in the case of the angle-ply laminate.

![Figure 5. Crack tip opening displacement for the cross-ply laminate.](image)

Table 2. Initial displacement jumps for the studied configurations of composite laminates.

|                | Cross-ply laminate, [90/0/90/0]_s | Angle-ply laminate, [(±60)]_s |
|----------------|-----------------------------------|-------------------------------|
| δ/2 [mm]       | 47.95                             | 50.338                        |

![Figure 6. Equivalent stress distribution on the cross-ply laminate for initial imposed displacement.](image)

![Figure 7. Equivalent stress distribution on the angle-ply laminate for initial imposed displacement.](image)
Figures 6 and 7 illustrate the equivalent stress distributions for the cross-ply laminate and for the angle-ply laminate, corresponding to the initial imposed displacement. The results show that for approximately the same crack tip opening displacement, the maximum values of the equivalent stresses of the cross-ply laminate have almost a double value compared to the angle-ply laminate. Therefore, it can be considered that the angle-ply laminate develops an improved behaviour to an opening fracture mode compared to the cross-ply laminate.

Moreover, the distributions of the equivalent stresses on the laminated composites are significantly different. In the case of the angle-ply laminate, the maximum equivalent stresses are visible on the exterior layers, while for the cross-ply laminate, the maximum values of the equivalent stresses occur at the adjacent layers of the crack tip.

3.1.2. Stress field distribution on the vicinity of the crack tip of the delamination growth. For an improved visualization of the stress field around the crack tip, a cross-section and a longitudinal section along the vicinity of the delamination growth are represented in figures 8 and 9, for both composite laminates analysed. Therefore, the equivalent stress distributions can be investigated on each layer of the composite laminates, and a symmetry with respect to the middle plane can be observed.

![Figure 8](image)

Figure 8. The stress field in the vicinity of the crack tip for the cross-ply laminate: (a) Cross-section; (b) Longitudinal section.

![Figure 9](image)

Figure 9. The stress field in the vicinity of the crack tip for the angle-ply laminate: (a) Cross-section; (b) Longitudinal section.
3.1.3. Traction-separation curves and ultimate opening displacement jumps. The investigation of the delamination growth is performed until the reactive forces can no longer withstand the separation of the cohesive surfaces. Therefore, corresponding to the ultimate reactive forces, the ultimate opening displacement jumps are determined for both configurations of composite laminates as a response to the ultimate imposed displacements. Figures 10 and 11 show the variation of the reactive forces with respect to the displacement jumps at the crack tip, representing the exponential traction-separation curves.

Analysing the ultimate imposed displacements for each laminate before the collapse or the total separation of the layers occurs, it can be observed that the angle-ply laminate withstands a higher value of the tensile displacement ($\Delta = 280 \text{ mm}$), compared to the cross-ply laminate ($\Delta = 175 \text{ mm}$).

**Figure 10.** Traction-separation curve of cross-ply laminate for ultimate displacement $\Delta = 175 \text{ mm}$.

**Figure 11.** Traction-separation curve of angle-ply laminate for ultimate displacement $\Delta = 280 \text{ mm}$.

**Figure 12.** Ultimate opening displacement jump for the cross-ply laminate, [mm].
Corresponding to the ultimate imposed displacement ($\Delta = 175$ mm), figure 12 illustrates the ultimate deformed shape of the cross-ply laminate before total separation of the cohesive surface and the ultimate opening displacement jump.

The data regarding the displacement jumps at the crack tip and the corresponding ultimate imposed displacements for the considered configurations are centralised in table 3.

**Table 3.** Ultimate displacement jumps for the studied configurations of composite laminates.

|                              | Cross-ply laminate, \([90/0/90]_s\) | Angle-ply laminate, \([\pm60]_s\) |
|------------------------------|--------------------------------------|---------------------------------|
| $\delta/2$ [mm]              | 191.91                               | 307.64                          |
| Ultimate imposed displacement, $\Delta$ [mm] | 175                                  | 280                             |

3.1.4. Equivalent stress distributions corresponding to ultimate delamination. Figures 13 and 14 illustrate the equivalent stress distributions on both composite laminates corresponding to the ultimate failure stage. The tendency of maximum equivalent stresses occurrence for the delamination growth is similar to the delamination onset. The evolution of the interlaminar damage is directed from the loaded edge towards the fixed end.

![Figure 13. Equivalent stress distribution on the cross-ply laminate for ultimate displacement, [MPa].](image)

![Figure 14. Equivalent stress distribution on the angle-ply laminate for ultimate displacement, [MPa].](image)

The maximum values of the equivalent stresses for the cross-ply laminate are higher compared to the angle-ply, taking into account that the corresponding imposed displacement is smaller for the cross-ply compared to the angle-ply. Therefore, the weak behaviour of the cross-ply laminate to a *Mode I* delamination type is demonstrated.
3.2. Effect of the adjacent layers of composite laminates on the delamination evolution

In order to investigate the influence of the adjacent layers on the delamination onset and delamination growth, two different configurations of multi-layered composites are analysed, namely $[0/+/0/+0/0]$ and $[0/+/0/-0/0]$. 38 numerical simulations were carried out, where the only variable parameter are the fibre orientations and the sign of the fibre orientation angles of the adjacent layers involved in the delamination process.

In Table 4 the opening displacement jumps for each configuration of laminated composites are presented.

| $\theta$ | Composite laminates with same fibre orientation angles on adjacent layers | Composite laminates with opposite sign of fibre orientation angles on adjacent layers |
|---------|-------------------------------------------------|-------------------------------------------------|
| 0       | $[0_{1x}]$                                      | $[0_{1x}]$                                      |
| 5       | $[0_{5x}+5/+/5/0_{5x}]$                         | $[0_{5x}+5/-5/0_{5x}]$                         |
| 10      | $[0_{10x}+10/+/10/0_{10x}]$                     | $[0_{10x}+10/-10/0_{10x}]$                      |
| 15      | $[0_{15x}+15/+/15/0_{15x}]$                     | $[0_{15x}+15/-15/0_{15x}]$                      |
| 20      | $[0_{20x}+20/+/20/0_{20x}]$                     | $[0_{20x}+20/-20/0_{20x}]$                      |
| 25      | $[0_{25x}+25/+/25/0_{25x}]$                     | $[0_{25x}+25/-25/0_{25x}]$                      |
| 30      | $[0_{30x}+30/+/30/0_{30x}]$                     | $[0_{30x}+30/-30/0_{30x}]$                      |
| 35      | $[0_{35x}+35/+/35/0_{35x}]$                     | $[0_{35x}+35/-35/0_{35x}]$                      |
| 40      | $[0_{40x}+40/+/40/0_{40x}]$                     | $[0_{40x}+40/-40/0_{40x}]$                      |
| 45      | $[0_{45x}+45/+/45/0_{45x}]$                     | $[0_{45x}+45/-45/0_{45x}]$                      |
| 50      | $[0_{50x}+50/+/50/0_{50x}]$                     | $[0_{50x}+50/-50/0_{50x}]$                      |
| 55      | $[0_{55x}+55/+/55/0_{55x}]$                     | $[0_{55x}+55/-55/0_{55x}]$                      |
| 60      | $[0_{60x}+60/+/60/0_{60x}]$                     | $[0_{60x}+60/-60/0_{60x}]$                      |
| 65      | $[0_{65x}+65/+/65/0_{65x}]$                     | $[0_{65x}+65/-65/0_{65x}]$                      |
| 70      | $[0_{70x}+70/+/70/0_{70x}]$                     | $[0_{70x}+70/-70/0_{70x}]$                      |
| 75      | $[0_{75x}+75/+/75/0_{75x}]$                     | $[0_{75x}+75/-75/0_{75x}]$                      |
| 80      | $[0_{80x}+80/+/80/0_{80x}]$                     | $[0_{80x}+80/-80/0_{80x}]$                      |
| 85      | $[0_{85x}+85/+/85/0_{85x}]$                     | $[0_{85x}+85/-85/0_{85x}]$                      |
| 90      | $[0_{90x}+90/+/90/0_{90x}]$                     | $[0_{90x}+90/-90/0_{90x}]$                      |

Figure 15 shows the graphical variation of the opening displacement jumps at the crack tip with respect to the fibre orientations of the adjacent layers involved in the delamination process, for both analysed configurations of laminated composites. The variations are in good agreement with the results available in the literature [14].
Figure 15. The variation of the Mode I opening displacement with respect to the fibre orientation angle of the adjacent layers.

The results show that composite laminates whose configuration has the same sign on the adjacent layers are more prone to delamination growth than the laminated composites with opposite sign of fibre orientations on the adjacent laminas. The highest values of the opening displacement jumps are identified in the interval $\theta = 10^\circ - 45^\circ$, reaching a maximum value for $20^\circ$ in the case of the $[0_5/+\theta/+\theta/0_5]$ composite laminate and for $25^\circ$ in the case of the other configuration, $[0_5/+\theta/-\theta/0_5]$.

Moreover, the variation of the Mode I opening displacement with respect to the orientation angles is very similar with the variation of the Poisson’s ratios, the highest values being identified for the same interval. Figure 16 shows the graphical representations of the in-plane and flexural major Poisson’s ratios with respect to the fibre orientation angles.

Figure 16. Analytical prediction of in-plane and flexural Poisson’s ratio variation of composite laminates with respect to the fibre orientation angles: (a) In-plane Poisson’s ratio; (b) Flexural Poisson’s ratio.
The mismatch of the Poisson’s ratios between the adjacent laminas may imply the occurrence of the interlaminar stresses, which can lead to delamination failure. The composite laminates with high values of Poisson’s ratios can be more exposed to a Mode I delamination type.

Therefore, a prediction of the interlaminar damage evolution of composite laminates based on the variation of the Poisson’s ratio with respect to the fibre orientation angle can be considered.

4. Conclusions
The paper presents a comparative analysis between a cross-ply laminate \([90/0/90_2]_S\) and an angle-ply laminate \([\pm 60_3]_S\) regarding the delamination onset and delamination growth. The results obtained are presented in terms of the opening displacement jumps at the crack tip and equivalent stress distributions for an initial imposed displacement. In order to enable the visualization of the stress field distribution on the vicinity of the crack tip of the delamination growth, a cross-section and a longitudinal section for each composite laminate is represented.

The analysis is performed up to the final failure, the delamination growth being presented until the reactive forces can no longer withstand the separation of the cohesive surfaces of the adjacent layers involved in the interlaminar damage process. Therefore, corresponding to the ultimate reactive forces, the ultimate opening displacement jumps are determined as a response to the ultimate imposed displacements. The exponential traction-separation curve, the ultimate equivalent stress distributions are presented for both configurations of the composite laminate. The results show that the angle-ply laminate withstands a higher tensile displacement \((\Delta = 280\,\text{mm})\), compared to the cross-ply laminate \((\Delta = 175\,\text{mm})\). Therefore, the weak behaviour of the cross-ply laminate to an opening fracture mode is observed. Moreover, the investigation of the effect of the adjacent layers on the delamination growth of the composite laminates is performed. Different configurations of multi-layered composites, such as \([0_3/\pm \theta/\pm \theta/0_3]\) and \([0_3/\pm \theta/-\theta/0_3]\) are analysed. The influence of the sign of the fibre orientation angles of the adjacent layers is also studied. The results are presented in terms of the variations of the opening displacement jumps with respect to the fibre orientation angles. The graphical illustrations obtained show similarities with the variation of Poisson’s ratio with respect to the fibre orientation. Therefore, the prediction of the delamination onset and growth can be correlated with the mismatch of the Poisson’s ratio of the adjacent laminas, which may involve significant interlaminar stresses.

5. References
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