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PROGRESSIVE FAILURE ENVELOPES FOR COMPOSITE LAMINATES

BY

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Abstract. A progressive failure analysis for composite laminates is carried out in the paper, based on a failure criteria initiation and a failure evolution law. The maximum strains failure criterion is selected and the material stiffness discount procedure is used as method to investigate the damage evolution.

Four cases of specially orthotropic composite laminates with different configurations are analysed: cross-ply, angle-ply, balanced and quasi-isotropic laminates. The multi-layered elements are selected in such a way that the influence of fibre orientations on the type of failure which may occur, can be noticed at a macromechanical scale.

The results are presented in terms of comparative representations of progressive failure envelopes, according to the plies failure stages, for each analysed composite laminate.

Keywords: composite laminates; failure stages; failure envelope; progressive failure; stiffness discount method.

1. Introduction

The unidirectional fibre reinforced polymeric (FRP) composite laminates refer to layered structures, made of two or more composite laminas

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stacked together, with the same or different fibre orientations. The laminated composites provide the possibility of tailoring the stiffness and strength of the composite element in the needed direction (Daniel & Ishai, 2006).

The progressive failure analysis is based on defining a failure criterion initiation and a failure evolution law (Hinton *et al.*, 2004). The failure initiation corresponds to the first rupture of the lamina which may occur in a composite laminate under loading. Moreover, it is similar with the moment of the initiation of the material stiffness degradation. The failure evolution law defines a path according to which the material stiffness will be degraded. The material stiffness degradation method, known as the ply discount method (Barbero, 2011), and the continuum damage mechanics are two of the most used processes in the investigation of progressive failure.

The failure envelope of the composite laminates is represented by the domain bounded by the tensile and compressive strengths in the principal material axes of the composite laminas. The progressive failure envelope can be identified as the domain of the strength safety behaviour after the failed plies are discounted from the composite laminate stiffness.

2. Case studies

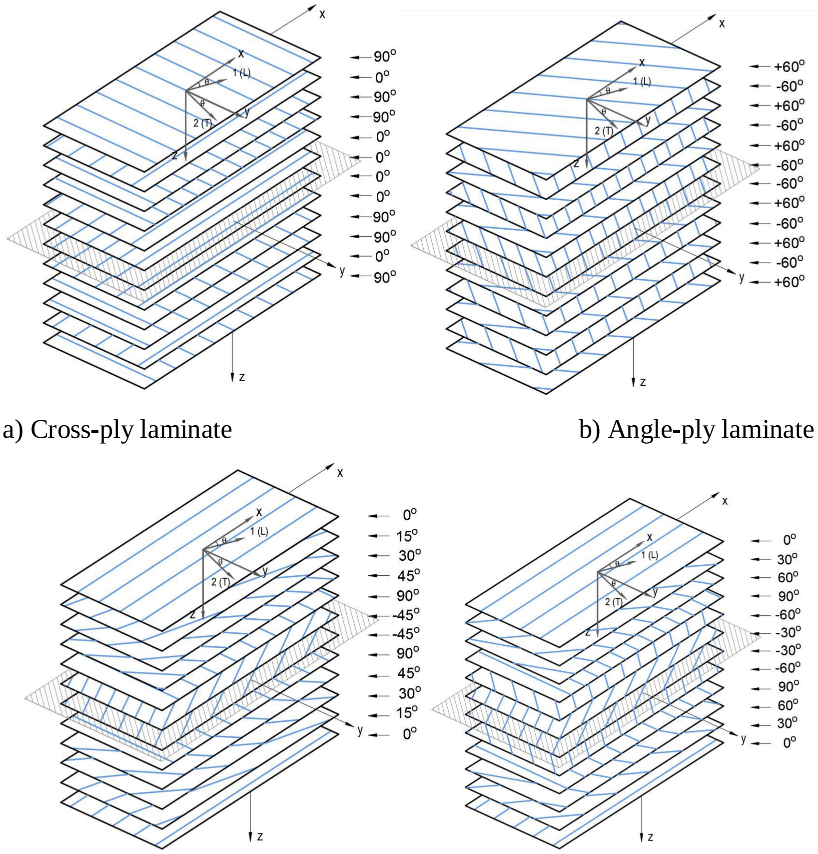
The following configurations of symmetrical specially orthotropic multi-layered laminates are considered: $[90/0/(90)_2/(0)_2]_s$ cross-ply laminate, $[(\pm 60)_3]_s$ angle-ply laminate, $[0/15/30/45/90/-45]_s$ balanced laminate and $[0/30/60/90/60/30]_s$ quasi-isotropic laminate, as shown in Fig. 1. The composite laminates are selected in such a way that the type of failure which might occur under loading can be characterised, depending on the fibre orientation configurations of laminates. The elementary laminas which form the composite laminates are made of S glass fibres embedded in an epoxy matrix.

The cross-ply laminates are defined as the laminates which have only fibre orientation angles of 0° and 90°, while the angle-ply laminates consist of plies oriented only at $+\theta$ and $-\theta$ directions (Kaw, 2006; Jones, 1999).

The balanced laminates are specially orthotropic multi-layered composites, made of an equal number of equal thickness laminas oriented at $+\theta$ and $-\theta$ directions (Gibson, 2012). The quasi-isotropic composite laminates are defined as symmetric laminates (Herakovich, 1997) which satisfies the following relation:

$$\Delta\theta = \frac{\pi}{N}, \tag{1}$$

where: $\Delta\theta$ is the angle between the fibres orientation and $N \geq 3$ – the number of layers in the laminate.



a) Cross-ply laminate b) Angle-ply laminate

c) Balanced laminate d) Quasi-isotropic laminate

Fig. 1 – The multi-layered composites considered in the case study (Dupir(Hudişteanu) *et al.*, 2016).

3. Failure Criterion

The failure criterion used in the case study is the maximum strain failure criterion. According to it, the initiation of failure occurs when the strains along the direction of the fibres exceed the corresponding ultimate strains of the laminas:

$$\begin{aligned} -\varepsilon_{Lc} < \varepsilon_1 < \varepsilon_{Lt}; \\ \varepsilon_{Tc} < \varepsilon_2 < \varepsilon_{Tt}; \\ -\gamma_{LTf} < \gamma_{12} < \gamma_{LTf}, \end{aligned} \tag{2}$$

where: ε_{Lt} , ε_{Lc} are the ultimate tensile strains in the longitudinal and transverse direction, respectively; ε_{Tt} , ε_{Tc} – the ultimate compressive strains in the longitudinal and transverse direction, respectively; γ_{LTf} – the ultimate shear strain in the (LT) plane.

The maximum strains $(\varepsilon_1, \varepsilon_2, \gamma_{12})$ along the principal material axes, corresponding to a stress σ_x , can be evaluated as follows:

$$\varepsilon_1 = \frac{\sigma_x}{E_1}\left(\cos^2\theta - \nu_{12}\sin^2\theta\right);$$
$$\varepsilon_2 = \frac{\sigma_x}{E_2}\left(\sin^2\theta - \nu_{21}\cos^2\theta\right); \quad (3)$$
$$\gamma_{12} = \frac{\sigma_x}{G_{12}}\sin\theta\cos\theta,$$

where: σ_x is the direct stress in the x direction; θ represents the fibre orientation angle; E_1 , E_2 and G_{12} are the axial and shear moduli of elasticity along the principal material axes, respectively.

According to the maximum strain criterion, the failure envelope of the S glass fibres and epoxy matrix composite lamina is represented by a parallelogram, as shown in Fig. 2 (Ţăranu *et al*., 2013), where: f_{Lt} , f_{Tt} are the tensile longitudinal and transverse strength of the composite lamina, respectively; f_{Lc} , f_{Tc} represent the compressive longitudinal and transverse strength of the composite lamina, respectively.

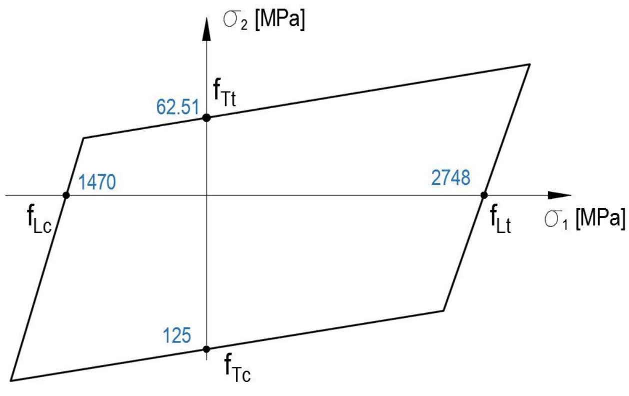


Fig. 2 – Failure envelope of composite lamina according to maximum strains failure criterion.

4. Progressive Failure Envelopes

In order to represent the progressive failure envelopes of the composite laminates, a progressive failure analysis was carried out in (Dupir (Hudi□teanu) et al., 2016). In Table 1 are presented the plies failure stages of the multi-layered composites, loaded under a longitudinal tensile strain of 0.06 mm/mm.

Table 1
Failure Stages of the Analysed Composite Laminates

Composite Laminate	Failure stages	Number of the failed plies
Cross-ply laminate	Ist failure stage	6 layers (θ = 90°)
	IInd failure stage	6 layers (θ = 0°)
Angle-ply laminate	I failure stage	12 layers (θ = ±60°)
Balanced laminate	Ist failure stage	2 layers (θ = 90°)
	IInd failure stage	2 layers (θ = ±45°)
	IIIrd failure stage	2 layers (θ = 30°)
	IVth failure stage	4 layers (θ = 15°)
	Vth failure stage	2 layers (θ = 0°)
Quasi-isotropic laminate	Ist failure stage	2 layers (θ = 90°)
	IInd failure stage	4 layers (θ = ±60°)
	IIIrd failure stage	4 layers (θ = ±30°)
	IVth failure stage	2 layers (θ = 0°)

The progressive failure envelopes for the studied multi-layered elements, after each failure stage of the composite layers are illustrated in Figs. 3,...,6.

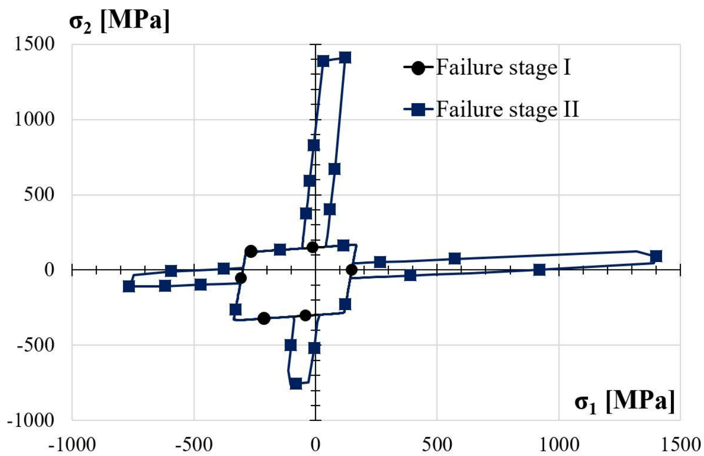


Fig. 3 – Progressive failure envelope for the cross-ply laminate.

The progressive failure of the $[90/0/(90)_2/(0)_2]_s$ cross-ply laminate occurs in 2 failure stages, as shown in Fig. 3, while the $[(\pm 60)_3]_s$ angle-ply laminate has a sudden failure of all laminas, as illustrated in Fig. 4.

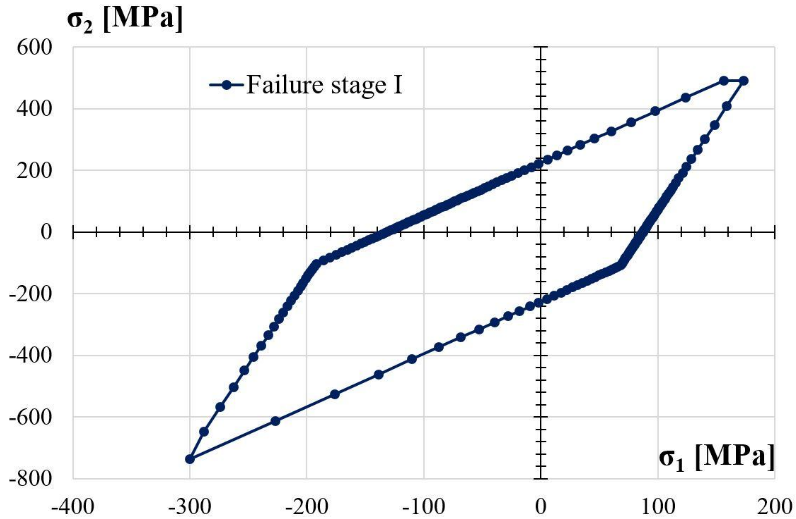


Fig. 4 – Progressive failure envelope for angle-ply laminate.

In case of the balanced and the quasi-isotropic laminates the failure occurs gradually, in 5 and 6 stages respectively as shown in Figs. 4 and 5.

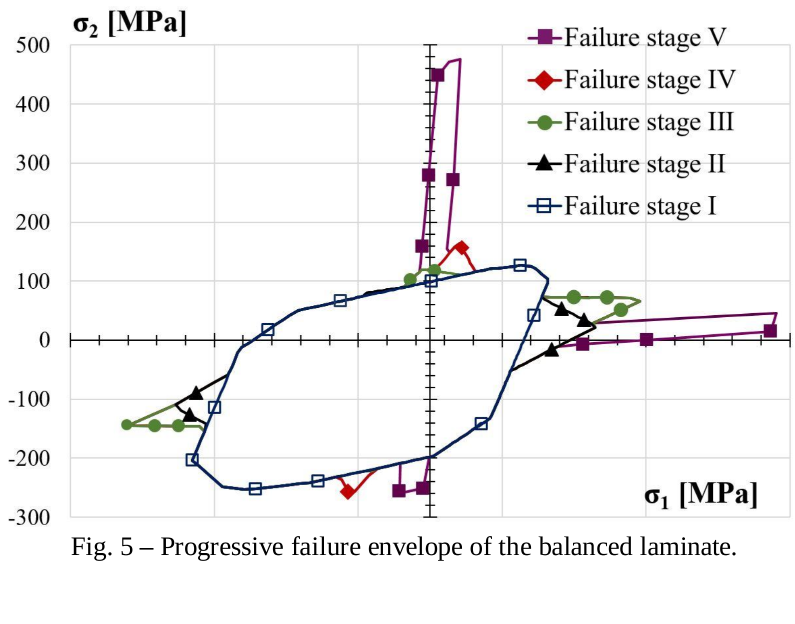


Fig. 5 – Progressive failure envelope of the balanced laminate.

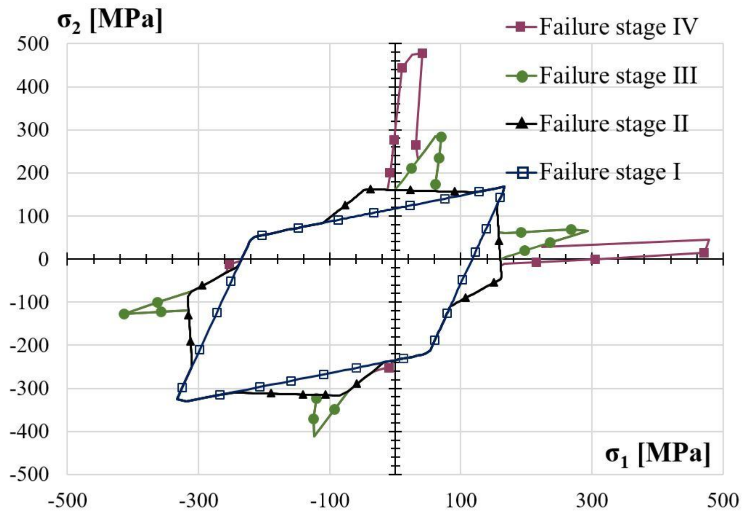


Fig. 6 – Progressive failure envelope for quasi-isotropic laminate.

A comparative representation of the specially orthotropic composite laminates at first ply failure (FPF) is illustrated in Fig. 7.

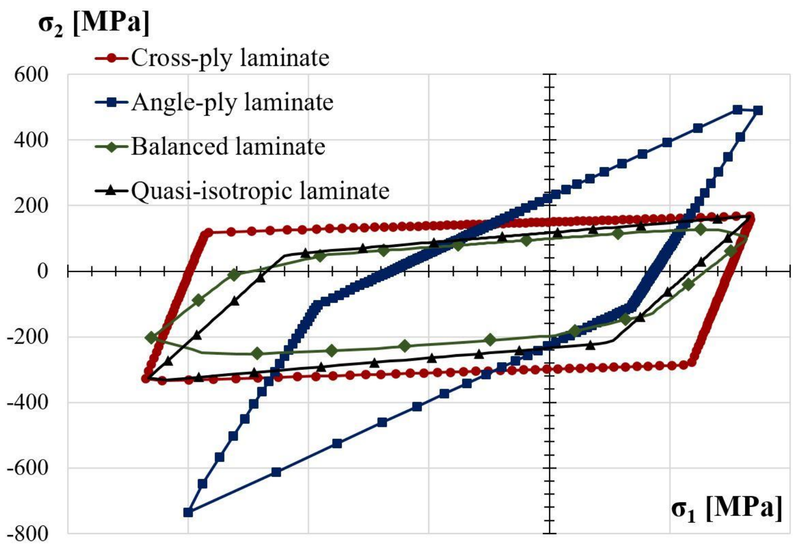


Fig. 7 – Comparative analysis of FPF envelope for the analyzed composite laminates.

As the illustrations show in Fig. 3 and Figs. 5 and 6, the first failure envelopes caused by the first breakage stage, provide the lowest capable stresses, but an extensive domain of strength safety behaviour, having the shape of a parallelogram. The first plies failures are represented by the weakest layers, which generally have the fibres oriented perpendicular to the loading direction. The highest stresses are reached in the layers which have the fibres orientations identical or close to the direction of loading. Their failure envelope is tailored and enlarged only in direction of the fibres orientation.

5. Conclusions

A progressive failure analysis was performed, in order to represent the progressive failure envelopes for composite laminates with different configurations. The analysis was carried out based on the maximum strain failure criterion and on the material stiffness degradation method.

The progressive failure envelopes illustrated for the studied cases of specially orthotropic composite laminates predict the sudden or gradual failure which occur, based on the number of fracture stages.

The catastrophic failure of the angle-ply laminate can be considered a dangerous condition, since the initiation of first ply failure corresponds to the total collapse of the laminate. Suitable configurations for gradual failure of composite laminates are represented by the balanced and quasi-isotropic laminates, because they fail in progressive fracture stages. Therefore, the orientation of fibres is an important parameter to consider when mechanical behaviour of composite laminates up to failure is analysed.

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ANVELOPE DE CEDARE PROGRESIVĂ ALE STRATIFICATELOR COMPOZITE

(Rezumat)

Este prezintată o analiză a cedării progresive a stratificatelor compozite, ce are la bază folosirea unui criteriu de inițiere a cedării şi a unei legi de evoluție a degradărilor. Se utilizează criteriul deformațiilor specifice maxime, iar metoda reducerii rigidității materialelor este folosită drept tehnică de investigare a evoluției degradărilor.

Sunt analizate patru cazuri de stratificate special ortotrope, având configurații diferite, şi anume: stratificat în cruce, stratificat unghiular, echilibrat şi cvasi-izotrop. Elementele stratificate sunt selectate în aşa fel încât să se poată remarca influența orientării fibrelor asupra modului de cedare ce ar putea apărea la nivel macromecanic. Rezultatele sunt prezentate comparativ, sub forma unor anvelope de cedare progresivă, pe etape de cedare ale lamelelor, pentru fiecare stratificat compozit analizat.