DAMAGE EVOLUTION IN THIN AND THICK-PLY REGIONS OF NCF THIN-PLY LAMINATES UNDER OFF-AXIS UNIAXIAL LOADING

G. Guillamet*[1], A. Turon[1], J. Costa[1], J. Renart[1]

[1]*Analysis and Advanced Materials for Structural Design (AMADE), Polytechnic School, University of Girona, Campus Montilivi s/n, 17071 Girona, Spain*
* *Corresponding Author: gerard.guillamet@udg.edu*

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Abstract

The present paper presents an experimental investigation of the evolution of damage in composite laminates manufactured using NCF thin-ply laminates. The objective is to analyse the damage evolution in a thin-ply quasi-isotropic laminate under different off-axis loadings. The main feature of the analysed laminate relies on its stacking sequence, which consists on two regions with or without ply clustering. The damage occurrence and evolution for both regions has been analysed by monitoring the specimen from the free-edge. The results show that although the laminates are isotropic in stiffness they are highly anisotropic in strength. Moreover, the use of thin-plies delay and in some cases even suppress some damage mechanisms before specimens failure.

1. Introduction

New available manufacturing technologies allow to produce plies thinner than the ones commonly used. Due to the growing demands on aeronautical and aerospace industry to enhance the mechanical behaviour, thin-ply Non-Crimp Fabrics (NCFs) have been developed and proposed as a new material, in front of the traditional unidirectional (UD) and fabrics. One of the manufacturers is Chomarat which produces the C-Ply^{TM}multiaxial carbon reinforcement [1]. This product consists on a bi-angle thin-ply NCF based on laminates such as [0/25] or [0/45].

Although few research works are available in the literature focused on the mechanical response of thin-ply NCF materials, the potential contribution of this new material has been shown recently. In a recent study of the authors [2], the influence of thin plies on the matrix cracking and free-edge delamination onset have been analysed. The numerical results showed a big improvement of delamination and transverse cracking resistance. More recently, Arteiro et al. [3] carried out an experimental campaign on plain strength, center-notched, open-hole and bearing tests in tensile and compression loadings in thin-ply NCF laminates demonstrating again the ability to suppress or delay some damage mechanisms. However, further experimental research is necessary to understand the mechanical behaviour of the aforementioned material.

The objective of this work is to analyse the damage evolution in a thin-ply quasi-isotropic laminate under different off-axis loadings. The main feature of the analysed laminate relies on its stacking sequence, which consists on two regions with and without ply clustering. The damage occurrence and evolution for both regions has been analysed by monitoring the specimen from the free-edge. The results show that although the laminates are isotropic in stiffness they are highly anisotropic in strength. Moreover, the use of thin-plies delay and in some cases even suppress some damage mechanisms before specimen's failure.

2. Methodology

2.1. Material and specimens

The material investigated in this study is a carbon/epoxy non crimp fabric (NCF) bi-angle C-Ply^{TM}from Chomarat. This material is a carbon multiaxial product or NCF made up of two unidirectional plies [0/-45] which are mechanically sewn together. The material was pre-impregnated by Aldila using AR2527 epoxy system. Table 1 summarizes the ply properties of the material.

E_{11}	E_{22}	ν_{12}	G_{12}
110.0GPa	7.4GPa	0.3	4.2GPa

Table 1. Material properties for T700/AR2527 thin-ply C-Ply^{TM}[3]

The proposed lay-up for this work is $[(0/-45)/(45/0)/(90/45)/(-45/90)]_S$. Note that the ply scheme is symmetrical by bi-angle layer of [0/-45], but not symmetrical by unidirectional ply. This laminate is 16-ply thick with a nominal total laminate thickness of 1.3 mm and a nominal ply thickness of 0.08 mm. In order to study the effect of the loading direction on the lay-up, specimens were cut from the panel in three different directions, where the longitudinal direction of each specimen was the loading direction during the tests. Table 2 show the resulting lay-ups,

	rot.	Stacking Sequence	θ	α	β	δ
L1	0	$[(0/-45)/(45/0)/(90/45)/(-45/90)]_S$	0	-45	45	90
L2	-45	$[(45/0)/(90/45)/(-45/90)/(0/-45)]_S$	45	0	90	-45
L3	-90	$[(90/45)/(-45/90)/(0/-45)/(45/0)]_S$	90	45	-45	0

Table 2. Stacking sequences due to different off-axis loadings

where θ, α, β and γ refer to the orientation of the different plies schematically represented in Figure 1. There is ply clustering (adjacent plies with the same fibre orientation) for layers 10 to 15 (θ, β, and δ), while the rest of the lay-up has no ply clustering. Thus, two regions are distinguished hereafter referred to as *THICK* (with ply clustering) and *THIN* (without ply clustering).

2.2. Test set-up and procedure

An experimental campaign consisting on a series of tensile tests was performed. First of all, the edge of all specimens were polished in order to reduce the advancement of the damage due to the

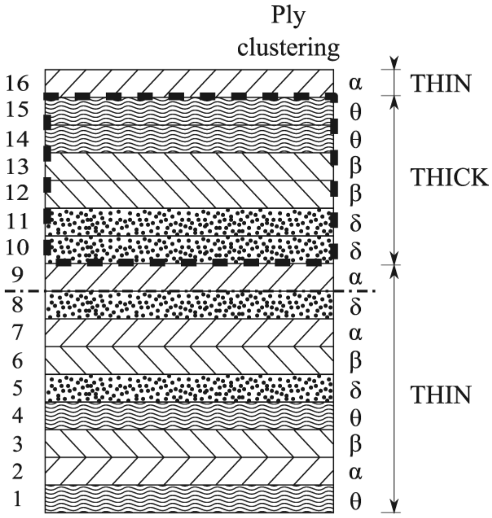

Figure 1. Global configuration of the lay-up

free-edge effect [4]. All experimental tensile tests were performed using an hydraulic machine MTS 810 ($250kN$). The speed of the machine was set to $0.5mm/min$ under displacement control. In order to define the critical strain for each failure mechanism an axial extensometer with a gage length of $25mm$ was used. A digital camera (Canon EOS 550D with MACRO lens of $100mm$) was set in front of the specimen's edge in order to monitor the different failure mechanisms at free-edges. The working distance (defined between the specimen edge and the support of the camera) was set between 300 and $320mmm$ for all the tests. That means a work specimen length about $50mm$ in order to have a proper monitoring of failure mechanisms into this length. The specimens tested were from three batches of three specimens per batch which results a total of nine specimens. All the tensile tests were based on the ASTM Standard [5]. The repetitiveness of each test is three in order to have feasible results for each staking sequence.

3. Results and discussion

The damage initiation and growth were analysed monitoring the specimen from the free-edge. Three different failure mechanisms were analysed: transverse cracking (TC), delamination triggered by matrix cracks (MCID) and free-edge delaminations (FED). The damage visible from the the free-edge of each specimen for an applied strain of 1.46% is shown in Figure 2. It is worth remarking that the damage initiation and its development were different for each off-axis load and region.

Figure 2. Damage occurred at the free-edge (Applied strain of 1.46%)

The first failure mechanism to appear was transverse cracking (TC) and was observed at those layers oriented at 90°. Table 3 shows the critical strains for TC at both regions. It can be seen that the THICK region TC appeared earlier than in the THIN region.

	THICK region		THIN region	
	Average strain [%]	stdev [%]	Average strain [%]	stdev [%]
L1	1.0523	0.0590	1.3932	0.0615
L2	0.8791	0.1277	-	-
L3	1.2530	0.1071	1.8114	0.0963

Table 3. Critical strains for onset of transverse cracking

Therefore, it was observed that the onset of TC at THIN regions was delayed and it occured at high strain loads close to laminate failure. For the case of laminate *L*45, TC was not observed at THIN region due to the highly progression of the damage at THICK region.

Delaminations triggered by matrix cracks (MCID) appeared once transverse cracks were present in the plies. Table 4 shows the critical strains for the onset of MCID for each laminate. These results show that MCID was drastically reduced at THIN region or in some cases it was even suppressed. The thin plies increase the in-situ effect for adjacent layers and reduce the onset of delaminations. It was also observed that this failure mechanism is very critical because it can potentially accelerate the laminate failure.

	THICK region		THIN region	
	Average strain [%]	stdev [%]	Average strain [%]	stdev [%]
L1	1.1814	0.0770	-	-
L2	1.0269	0.1286	-	-
L3	1.5162	0.1060	-	-

Table 4. Critical strains for onset of induced delaminations due to matrix cracks

Free-edge delaminations are also analysed, Table 5 shows the critical strains for the onset of free-edge delaminations (FED) for each lay-up and region. It is worth remarking that the presence of FED was only observed for laminates *L*0 and *L*90 and they appeared at both regions. Laminate *L*90 showed clearly evidences of FED whereas, *L*0 showed a combination of FED and MCID. It can also been concluded that the onset of FED at THICK region take place prior to the THIN region.

	THICK region		THIN region	
	Average strain [%]	stdev [%]	Average strain [%]	stdev [%]
L1	1.2670	0.1210	1.3980	0.0240
L2	-	-	-	-
L3	1.7032	0.0515	1.8424	0.1275

Table 5. Critical strains for onset of free-edge delaminations

4. Conclusions

The onset and progression of damage mechanisms in a thin-ply bi-axial non-crimp fabric laminate under different off-axis loadings have been studied. The ply sequence was devised so that a THIN region could be distinguished from a THICK region (where plies were clustered). Specimens from the same panel, which was elastically isotropic in the laminate plane, were extracted following different orientations (0°, 45° and 90°). Then, the specimens were tested under an uniaxial load while the damage mechanisms were investigated by optically monitoring the free edge of the specimen. Strains for the onset of transverse matrix cracking (TC), of delaminations appearing from matrix cracks (MCID) and of free-edge delaminations (FED) were quantified, as well as their initial density.

The experimental results provided evidence that the damage mechanisms in the THIN region are clearly delayed, if not suppressed, with respect to its occurrence in the THICK region. It was observed that specimens with clustered transverse plies exhibit earlier damage onset, in agreement with the in-situ strength theories that predicts a decreasing ply strength as the ply thickness increases.

A proper tailoring of the laminate ply sequence to fully exploit the advantageous mechanical capabilities of thin plies, requires the use of a set of refined, physically-based, failure criteria at the ply level. Such failure criteria should not only account for the ply characteristics (orientation, thickness) but also be sensitive to the location of the ply in the laminate. Another conclusion from this work is that any potential optimization of the stacking sequence performed for one loading direction can have a entirely different effect under a different loading direction. Therefore, the dramatic enhancement of design freedom associated with the use of thin plies (and their combination with standard thickness plies) should be counterbalanced with improved design design tools able to anticipate stacking sequence effects at any orientation.

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