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Damage occurrence at edges of non-crimp-fabric thin-ply laminates under off-axis uniaxial loading

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ABSTRACT

Thin-ply based laminates are a promising development in composite materials and are expected in the near future to outperform conventional laminates in mechanical performance. A rational design with thin plies requires understanding the effect of ply thickness on each damage mechanism. This paper presents an experimental investigation into damage occurrence in a quasi-isotropic laminate made from thin-ply, bi-axial, Non-Crimp-Fabric (NCF), under different off-axis uniaxial loadings. The NCF layers are positioned through the laminate thickness creating two regions, namely THICK and THIN (with and without ply clustering). Then, the onset and progress of three damage mechanisms (transverse matrix cracking, matrix crack induced delamination and free-edge delamination) for both regions are analyzed by monitoring the specimen's free-edge. The results show that the critical region where damage occurs is that with ply clustering (THICK), whereas delamination originating from matrix cracks or free edge effects are delayed or even suppressed in the THIN region.

1. Introduction

New manufacturing technologies for composite laminates are emerging and producing thinner than conventional plies [1,2]. One example is the *spread tow thin-ply technology*, which produces flat, straight plies until a dry ply thickness as low as 0.02 mm is reached [3].

Recent research publications report on the advantages of using thin-ply laminates. One pioneering work was carried out by Sihn et al. [2], who performed an experimental campaign comparing the mechanical properties of conventional laminates to so-called thin-ply laminates. In this study they observed that, without special resins, the thin-ply laminate composites suppress micro-cracking, delamination and splitting damage for static, fatigue and impact loadings. Another interesting work by González et al. [4], focused on the effect of ply clustering in low-velocity impact loading. In this experimental study, the authors concluded that ply clustering (thicker plies), reduces the damage resistance of a structure. More recently, a numerical study by Camanho et al. [5] analyzed the influence of ply thickness on the *in situ strengths* [6], as well as on the free-edge delamination onset of a specimen under tension. The numerical results showed a significant improvement in transverse cracking and delamination resistance when using thin-ply based laminates.

For a given total thickness of the laminate, the use of thin-plies in the design entails, as opposed to conventional plies, a higher number of plies. Therefore, thin-ply Non-Crimp Fabrics (NCFs), which group two to four plies together [3], have been proposed as an alternative to conventional unidirectional (UD) tapes and crimp textile configurations. NCF provides numerous benefits for laminate design, such as easy laminate homogenization and simpler ply stacking, a reduction in processing time, cost, waste and stacking errors [7,8].

Few published works make reference to the mechanical response of thin-ply NCF's. However, the potential contribution of this new material has been highlighted, for instance Tsai et al. [9] demonstrated a remarkable improvement in stiffness and strength of NCF thin-ply laminates for open-hole and compression after impact (CAI) tests. More recently, Arteiro et al. [10] carried out a fully experimental campaign of plain strength, center-notched, open-hole and bearing tests in thin-ply NCF laminates which demonstrated the ability of thin-ply laminates to suppress or delay some damage mechanisms and increase the strength of the laminate. However, none of these research works focused on the onset of damage mechanisms at the free-edge or their subsequent development. Thus, in order to achieve a comprehensive and solid understanding of the mechanical behavior of these

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materials, which is a requirement to reach an optimum mechanical design, further experimental research is necessary.

As advanced composites are frequently used in strength-critical applications which must withstand loads in different directions, several studies which analyze the occurrence of damage in composite laminates using different off-axis loadings have been published. For instance, Sun and Zhou [11] found that due to the edge effects, a quasi-isotropic laminate (elastically isotropic in the laminate in-plane) is highly anisotropic in strength. Other authors, such as Varna et al. [12], studied the off-axis problem from a different angle. They analyzed the occurrence of damage in a lay-up by examining various orientations of a particular ply without changing the orientation of the others. They found that matrix cracking was observed in the ply under transverse tension stresses and that the laminate elastic moduli underwent changes with the crack density. On the other hand, compression stresses normal to the fiber direction altered the elastic moduli, even though matrix cracking was not observed. Nevertheless, the development of damage mechanisms and the strength of thin-ply NCF laminates with different off-axis loadings have not yet been investigated.

The objective of this work is to conduct an experimental campaign analyzing damage development in a quasi-isotropic laminate made of thin-ply NCF under different off-axis loads. The laminate studied has a specific stacking sequence, consisting of two regions or sub-laminates with and without ply clustering, identified in this paper as THICK and THIN regions, respectively. Damage occurrence and its evolution for both regions is analyzed utilizing optical monitoring of the specimen's free-edge. Moreover, the same laminate is tested with different off-axis loads to evaluate the strength of the laminate in each direction.

The content of this paper is structured as follows. Firstly, the methodology of the experimental campaign is presented together with a brief description of the material, the specimen characteristics and the test procedure. Then, the results of the stress–strain relations are presented along with the occurrence of damage mechanisms at the free-edge of the specimen. Finally, the results are discussed in light of the influence of the ply clustering and the direction of the off-axis loading.

2. Experimental

2.1. Material and manufacturing

The material investigated in this study is carbon T700 made up of two layers, 0° and −45° and commercialized by Chomarat: T700 C-Ply™ [0/−45] NCF. This material is manufactured with the *spread tow thin-ply technology* resulting in a total areal weight of 150 g/m^2 per bi-angle layer (2 × 75 g/m^2). The material was pre-impregnated by Aldila using the epoxy system AR2527. The elastic ply properties are $E_1 = 110$ GPa for the longitudinal modulus of elasticity, $E_2 = 7.4$ GPa for the transverse modulus, $G_{12} = 4.2$ GPa for the in-plane shear modulus and $\nu_{12} = 0.3$ for the longitudinal Poisson's ratio [10].

The stacking sequence is a $\pi/4$ quasi-isotropic configuration $[(0/-45)/(45/0)/(90/45)/(-45/90)]_s$. This lay-up is composed of 16 unidirectional plies (8 bi-angle layers) with a nominal ply thickness of 0.08 mm and a nominal laminate thickness of 1.3 mm. Note that, the ply configuration is not symmetric in terms of unidirectional plies, but symmetric in terms of a bi-angle layer of [0/−45]. This lay-up has no shear-extension coupling ($A_{16} = A_{26} = 0$) and the terms of the coupling matrix are zero ($B_{ij} = 0$).

The panel was manufactured at VX Aerospace using vacuum bagging. The specimens were obtained by cutting the panel with a diamond-coated disk at Airborne Composites.

2.2. Specimen characteristics

Specimens were cut from the panel in five different directions, as shown in Fig. 1, where the longitudinal direction of each specimen was the loading direction during the tests. Fifteen specimens, three specimens per batch or off-axis loading, were tested.

Taking the specimen loading direction as the 0° orientation for each specimen results in five different ply stacking sequences. They are labeled as L0, L23, L45, L68 and L90, which are rotated respectively over the panel 0°, −22.5°, −45°, −67.5° and −90°. The corresponding stacking sequences for each one are shown in Fig. 2. Two regions, or sub-laminates through the laminate thickness, are defined. The first region, hereafter referred to as THICK, has a ply clustering of two plies for those layers from 10 to 15, while in the second region, hereafter referred to as THIN, there is no ply clustering. Additionally, the sequence of mismatch angles (angles between adjacent layers) remains the same for all the lay-ups [13]. It is worth noting that, the sequence of mismatch angles includes mismatch angles between the $[0/-45]$ bi-angle layers.

Using the polar method applied to the Classical Laminate Theory (CLT) [14,15], it can be demonstrated that all laminates are isotropic in in-plane stiffness, but they are not isotropic in flexural stiffness. The polar plot of the two engineering constants of the laminate for each off-axis direction rotated over the panel is shown in Fig. 3, where E^{lam} and E_f^{lam} are respectively the in-plane and flexural laminate moduli; which are calculated by using the material elastic properties [10]. The proposed lay-ups, L0, L23, L45, L68 and L90, correspond to the 0°, 337.5°, 315°, 292.5° and 270° directions on the polar plot.

2.3. Test set-up

All experimental tests were performed under uniaxial tension using a MTS 810 servo-hydraulic testing machine (250 kN). The cross head displacement rate was set to 0.5 mm/min under displacement control. During the test, a digital camera (Canon EOS 550D with a 100 mm macro lens) was located in front of the specimen's edge to monitor the different damage mechanisms occurring at the free-edges [16]. The working distance (defined as the distance from the specimen edge to the support of the camera) was set between 300 and 320 mm, which implies monitoring a specimen length of about 50 mm. Additionally, an axial extensometer with a 25 mm gage length was used to measure the strain of the specimen during the test. The camera shots and the value of the strain from the extensometer were acquired simultaneously with a user-defined software.

All tensile tests were based on ASTM D3039/D3039M-08 [17]. The specimens' edges were polished with silicon carbide paper to

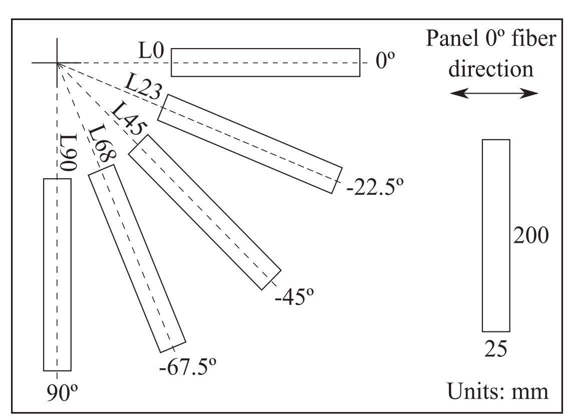

Fig. 1. Specimen cuts over the panel.