PSEUDO-DUCTILE RESPONSE OF ±45° CFRP SUBMITTED TO FLEXURAL LOADING

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Abstract
This work investigates analytically and experimentally the flexural pseudo-ductile response of symmetric ±45º angle-ply laminates consisting of unidirectional and continuous CFRP plies. Most of the existing literature about pseudo-ductility deals with uniaxial testing. To our knowledge, this is the first attempt to investigate the pseudo-ductile effects under three-point bending taking into account the higher degree of complexity introduced by the variation of the strain through the cross-section thickness. The analytical study takes into account the different behaviour of the material under tension and compression. Then, during the linear stage, the homogenised section technique allows to predict the neutral fibre deviation from the mid-height plane as well as the damage initiation mode and its position. The experimental description of the non-linear stage is developed thanks to the full normal strain field acquired by means of a DIC system and strain-rosettes that help to complete the data. Besides, the understanding of the damage initiation process and its evolution is studied by means of micrographic observations applying SEM technology. Finally, an optimisation procedure is proposed for determining the stacking sequences that minimise the bending-twisting coupling but favour the pseudo-ductile response with design purposes.

1. Introduction

±45º angle-ply laminates consisting of a large number of alternating layers usually present pseudo-ductility under uniaxial testing, mainly due to damage accumulation and matrix yielding that favors the tendency of the fibres to align with the loading direction. In general, high levels of deformation are generated before the failure of the material. This mechanism has been frequently analysed in the literature under the presence of uniaxial loads [1,2], but also it could be of great importance in cases of flexural loading [3,4]. The proposal of this work is to observe this phenomenon in the results of three-point experiments, since tensile and compressive loads are applied simultaneously in different regions of the cross section of the specimens.

2. Material and equipment

The material used is a pre-impregnated (prepreg) of epoxy matrix reinforced with unidirectional carbon fibers called M21E/34%/UD268/IMA-12K. This prepreg has direct application in the aeronautical industry, specifically in the primary structure of the Airbus A350 XWB. The properties obtained from its characterization [5-7] are summarised in Tables 1 and 2, in which the mean values of the elastic moduli E and the normal strengths f of a layer in principal directions are shown. The superscripts t and c refer to the cases of tensile and compressive loading, respectively. In addition, the material presents the average values of the interlaminar shear strength f_s, the Poisson coefficient υ_{12} and the shear modulus G_{12} displayed in the tables. From these material properties, the apparent value of the elastic moduli and strengths of ±45° layers under uniaxial loading ($E^t_{45°}$, $E^c_{45°}$, $f^t_{45°}$ and $f^c_{45°}$) can be obtained using the Classical Laminated Plate Theory (CLPT) [8] and the Tsai-Hill failure criterion [9].

Table 1. Strengths in principal directions depending on the load case and interlaminar shear strength (average values) [5-7].

f_1^t **[MPa]**	f_1^c **[MPa]**	f_2^t **[MPa]**	f_2^c **[MPa]**	f_{12} **[MPa]**	f_S **[MPa]**
2600.90	1356.20	56.07	200.00	103.93	46.65

Table 2. Elastic properties in principal directions depending on the load case (average values) [5-7].

E_1^t **[GPa]**	E_1^c **[GPa]**	E_2^t **[GPa]**	E_2^c **[GPa]**	G_{12} **[GPa]**	υ_{12}
177.56	97.03	11.84	7.46	5.15	0.39

The installations used to carry out this work are a hot platen press for curing composite materials, an universal testing machine which incorporates a three-point bending tool, a Scanning Electron Microscope (SEM) to observe the damage produced in the specimens and a Digital Image Correlation (DIC) equipment and strain rosettes for acquiring the deformation measurements during testing.

3. Procedure

The homogenized section technique (HST) developed in previous investigations [5-7] is applied to the problem of an angle-ply laminate formed by the aggrupation of ±45° layers and submitted to three-point bending [3-4]. This linear analytical model takes into account in its estimations the different response of the material under tensile and compressive loading. Under flexural loading, the main effect of this difference is the deviation of the neutral fibre (NF) from the mid-height plane and, therefore, the resultant non-symmetric strain and stress distributions. In order to measure the degree of influence, the HST defines the parameter $n = E^c_{45°} / E^t_{45°}$ that relates the elastic moduli under tension and compression. Then, a distance d between the NF and the mid-height plane is assumed. As the static moment of the homogenized cross-section with respect to the NF must be zero, the NF deviation can be obtained as $d = h\left(\sqrt{n}-1\right) / \left(2+2\sqrt{n}\right)$. In other side, the normal stress distribution due to the bending moment M is approximated considering a linear evolution defined by two parts, as $\sigma = My/I_z$ in the region submitted to compression and as $\sigma = My/nI_z$ in the compressed region. Defining y and z as the vertical and horizontal coordinates contained in the cross-section plane and with origin in the centre of the NF, then I_z is the z-inertia moment of the homogenised cross-section. In parallel, a review of the effect of the NF deviation and the different material response on the coupling membrane-moment and bending-twisting terms could be relevant. With this objective, CLPT is proposed to be used considering as reference plane the NF position (deviated a distance d from the mid-height plane) and the tensile and compressive properties of the material when the studied ply is situated either in the region submitted to tension or compression, respectively. Taking advantage of the equations given by the HST and the CLPT, a methodology for optimising the stacking sequences that minimises the bending-twisting coupling but favour the pseudo-ductile response is proposed.

Experimentally a $[+45\ -45]_{6S}$ laminate is chosen to be analysed [3,4] because its number of plies is high enough for minimising as far as possible the coupling between bending and torsional forces. Besides, based in the concept of in situ effects [10,11], alternating plies with different sign should require more energy to propagate damage than aggregating plies with same orientations. This should help the laminate to withstand higher levels of strain and, therefore, it should favour the existence of a longer non-linear phase. Plates with the desired configuration are fabricated in a hot platen press and from them, subsequently, prismatic specimens are machined with a rectangular cross section of average base b = 9.5 mm and height h = 5.5 mm. The resultant samples are tested using a three-point bending tool with a free span L = 25 mm. During the three-point bending tests, the load applied in the central cross-section is recorded. As well as the displacement δ and deformation ε fields are observed in the lateral plane of the specimen by means of a DIC equipment. In addition, the use of strain gages on the base of the central cross-section allows to ensure the accuracy of the deformations acquired by comparing the values obtained by the two types of techniques. SEM technology is used for locating the initiation and evolution of the damage.

4. Results and discussion

During testing the damage process is dominated by the bending moment. The lower and upper layers are the most deformed and, as in this material the normal tensile strength is smaller than the normal compressive strength, damage starts in the lower layer submitted to tension. Not only a single micro-crack parallel to the fibres could appear, but several micro-cracks could arise in its vicinity at the same time. After the damage initiation, the lower layer loses partially its ability to withstand load and the remaining layers must continue to support the increasing external load. Then, a chain reaction is produced in which the subsequent lower layers become the most deformed under tension and present micro-cracks similar to the ones previously described. As the damage propagates from bottom to top, the layers that have already failed tend to separate (delaminate) favoured by the curvature induced in the specimen. Along this process the NF position is shifted up due to accumulation of damage in the lower plies submitted to tension. This can be qualitatively intuited in the representation of the normal strain profile through the cross-section thickness acquired at different moments of the test (Fig. 1, in red). The stepped-shape is assumed to indicate local damage production. These steps in the strain diagram are attenuated from bottom to top during testing due to damage generalisation and accumulation, until they disappear in the last loading stages.

The apparent global mechanical response of the laminate presents a first linear stage followed by a non-linear phase due to damage accumulation that allows the composite to withstand high levels of strain. Both linear and non-linear behaviours can be clearly observed in Fig. 1 (in black), that shows for a representative specimen the evolution of the quotient P/b versus the maximum vertical displacement δ. Under flexural loading the strain varies through the thickness of the cross-section, so the observation of the pseudo-ductile effects at different heights could be of interest. In Fig. 2 the stress-strain evolution (with the normal stresses in absolute value) is represented at four heights defined along a vertical path of the central cross-section. The stresses are estimated using the HST that is a linear analytical model and, so that, the non-linear phase is just qualitatively represented. For assuring the correctness of the DIC experimental strains, the DIC strain at the bottom of the central cross-section is compared with the independent measurement given by the strain gage. Small differences are found, that are generally within 1% of deviation and in the worst case a 5% of deviation. The initial slope of the curves located in the tensed region coincide, finding the average value $E^{t}_{\pm 45^\circ} = 18.01$ GPa for the apparent tensile elastic modulus. Likewise, the points situated in the compressed region have similar linear-slopes equal in average to $E^{c}_{\pm 45^\circ} = 24.95$ GPa, considered to represent the apparent compressive elastic modulus. Different degrees of pseudo-ductility can be observed at different heights under flexural loading, finding a higher non-linear effect in the tensile region whenever the DIC-virtual gage is farther to the NF.

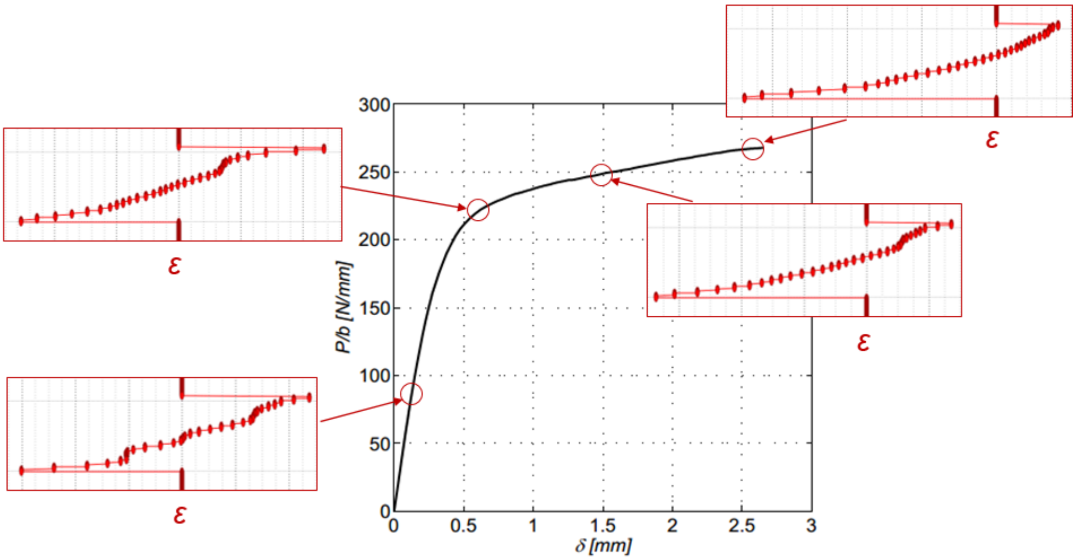

Figure 1. Load-displacement evolution in the central cross-section (in black) [3]. Normal strain profiles of the central cross-section at different moments of test (in red).

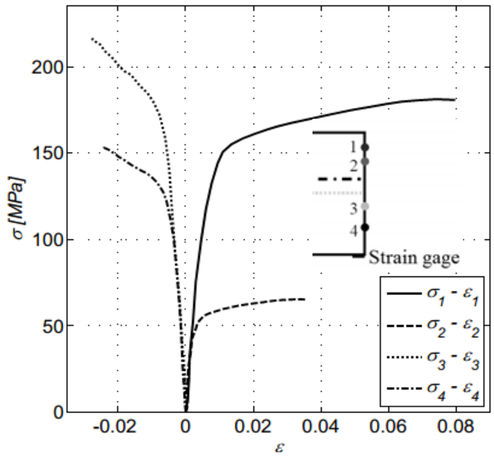

Figure 2. Stress-Strain evolutions at four different heights of a vertical central path [3].

In order to find an optimal configuration that could reduce the bending-twisting coupling but increases the pseudo-ductile response, the CLPT is evaluated considering a NF deviation d and a constitutive matrix for each ply that depends on the loading case (either tension or compression) [3]. The relevant terms of the symmetric $\mathbf{B}$ and $\mathbf{D}$ matrixes are defined following the nomenclature of Halpin [8]. A flexural problem is faced in which the bending moment induces not only bending curvatures and a slight level of torsion, but also membrane strains due to the deviation of the neutral fibre. Stacking sequences are considered to present a negligible bending-twisting coupling whenever the cross-term D_{16} is more than one order of magnitude smaller than the diagonal-term D_{11}. Additionally, in-plane strains are present in a damage mechanism dominated by the in-plane shear strains. In this work a higher level of in-plane strains is associated with a higher level of transverse strains and this is presumed to reduce the pseudo-ductile stage because it could be taken as a measurement of the proximity to the shear failure of the matrix. Therefore, higher values of B_{16} in comparison to B_{11} are considered to suggest lower levels of pseudo-ductility. The optimisation of the stacking sequence can be performed by minimising the objective function relating the ratios $|B_{16}/B_{11}|$, $|D_{16}/D_{11}|$ and total thickness h, which is taken into account for avoiding too thick specimens. Being both ratios equally weighted and the thickness ten times less influent, the best configuration of ±45° layers is found to be the laminate [-45 +45$_2$ -45 +45 -45$_2$ +45]$_S$ with relations $D_{16}/D_{11} = 2.13\cdot10^{-4}$ and $B_{16}/B_{11} = 2.17\cdot10^{-3}$. Other possibilities with different loss functions including different definition of weights could be explored, offering new perspectives on the design.

5. Conclusions

The combination of the analytical models and the experimental observations allows to understand and describe the pseudo-ductile flexural response of the ±45º angle-ply laminate. Then, several conclusions can be extracted from this work:

- Damage initiation in the form of matrix micro-cracking parallel to the fibres (no fibres rupture) and subsequent delamination as damage propagation mechanism are produced.
- A lifting of the NF appears during loading. This can be explained due to damage initiation in the lower layers and its subsequent propagation in ascendant direction (from bottom to top), what starts a redistribution mechanism of the excess increasing load in the remaining above plies that moves up the normal strain profile.
- The initial slope of the stress-strain evolution of fibres located in the tensed region of the cross-section coincide and it is equal to the apparent tensile elastic modulus $E^{t}_{\pm45^{o}}$. Likewise, the points situated in the compressed region have similar linear-slopes equal to the apparent compressive elastic modulus $E^{c}_{\pm45^{o}}$.
- Different degrees of pseudo-ductility can be observed at different heights under flexural loading, finding a higher non-linear effect in the tensile region whenever the DIC-virtual gage is farther to the NF.
- Higher transverse strains are presumed to reduce the pseudo-ductile stage because they could be taken as a measurement of the proximity to the shear failure of the matrix. Therefore, higher values of B_{16} in comparison to B_{11} are considered to suggest lower levels of pseudo-ductility.
- New perspectives of design are offered by means of optimizing a cost function that takes into account the coupling terms of matrixes **B** and **D**.

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