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Different response under tension and compression of unidirectional carbon fibre laminates in a three-point bending test

M.C. Serna Moreno *, A. Romero Gutiérrez, J.L. Martínez Vicente

Universidad de Castilla-La Mancha, Escuela Técnica Superior de Ingenieros Industriales de Ciudad Real, Instituto de Investigaciones Energéticas y Aplicaciones Industriales, Avenida Camilo José Cela s/n, 13071 Ciudad Real, Spain

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ABSTRACT

The apparent flexural elastic properties of laminates are traditionally obtained from experimental testing under the supposition of same behaviour under tension and compression. However, any composite generally presents different response when it is submitted to these loading cases. This work is focused on the three-point bending test parallel to the fibres, in laminates of unidirectional and continuous carbon fibre-reinforced epoxy. The purpose is to evaluate the influence on the test results of the dissimilar composite behaviour under tension and compression in the fibres direction. Analytical expressions for obtaining the normal and shear stress distributions in the most loaded section are derived using the technique of the homogenised section. Subsequently, a relation between the span and the thickness of the beam is determined for estimating whether the sample will present flexural or shear failure in the experiments. Parallelepiped specimens with two different thicknesses have been tested for reviewing both failure modes by means of optical microscopy. The experimental evidences are used to evaluate the correctness of the analytical model.

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1. Introduction

Besides the orthotropism of the material, another significant characteristic of composites is the difference in behaviour under tensile and compressive loads [1]. Both the elastic moduli and the strengths in the principal material directions are different under tension and compression. This fact makes composites more difficult to analyse than the traditional structural metallic materials. Which modulus is higher may depend on the relation between the fibre and the matrix stiffness. Nevertheless, this work does not focus on micromechanical aspects but on the analysis of the apparent stress–strain response under flexural loading with design purposes.

The study of the structural behaviour of laminates is motivated by the rapid expansion of composite materials, mainly in aerospace applications. In particular, carbon fibre-reinforced epoxy composites present many nonconventional structural mechanics which need detailed analysis. In this work the response in the fibres direction of unidirectional and continuous laminates is studied by means of three-point bending tests. The technique consists on applying a centred load on a simply supported beam. The specimen preparation and testing is relatively simple, but the results are sensitive to the geometry of the sample. Either bending or shear failure modes can appear depending on the relation between the span and the thickness of the beam. The standards determine the apparent flexural stiffness and strength [2,3] from the results of the specimens who develop bending failure modes. Meanwhile the normative calculates the interlaminar shear strength [4,5] taking into account the data from the cases with shear failure. In both situations the standards obtain the elastic properties assuming that the material presents the same response under tension and compression, despite it is typically different. This was clearly pointed out by Jones [6], who derived the elastic moduli and the maximum normal stresses in the regions submitted to tension and compression, respectively, in three-point and four-point bending tests from the equilibrium and constitutive relations. Similar deductions have been developed a posteriori by other researches [7,8] using analogous procedures. However, no previous study has been found for obtaining the shear stress distribution taking into account the different tensile and compressive behaviour. In this work we review analytically how the dissimilar response of the composite in the fibres direction affects not only to the normal but also to shear stress fields, applying the technique of the homogenised section. From these descriptions it is estimated whether

* Corresponding author.
E-mail address: mariacarmen.serna@uclm.es (M.C. Serna Moreno).
URL: http://www.uclm.es/area/mmedios/ (M.C. Serna Moreno).

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flexural or shear failure modes would be produced experimentally, depending on the relation between the span and the thickness of the specimen.

Furthermore, three-point bending tests are performed on parallelepiped specimens with the same width and length but two different thicknesses. The experimental observables are the applied load and the maximum tensile strain produced in the central section of the beam. In the post-process, the position where the damage is produced is analysed using an optical microscope. Both flexural and shear failure modes have been examined and the experimental data are used to review the validity of the analytical results.

The organisation of the paper is the following. Section 1 introduces, in general terms, the outline of the work. Section 2 describes the material, the geometry of the specimens, the test facility and the post-process tools. Section 3 shows the analytical description of the normal and shear stress fields considering the different behaviour of the composite under tension and compression. Section 4 explains the procedure followed to obtain the flexural and shear parameters from the experimental data, taking into account the theoretical estimations obtained in previous section. Finally, Section 5 gives the conclusions of the work.

2. Experimental background

Unidirectional and continuous carbon fibre-reinforced epoxy laminates are studied. The composite includes several plies stacked one over another by means of a hand lay-up process. Each ply is made from parallel carbon fibres pre-impregnated with an epoxy resin, commonly known as prepreg. The prepreg studied is composed of the Hexply® M21E resin and the unidirectional continuous high tensile strength fibres IMA-12K from Hexcel®. This material, named as M21E/34%/UD268/IMA-12K, is used in the primary structure of the Airbus A350 XWB. It has a resin content of 34% by weight and a fibre aerial weight of 268 g/m^2. Composite plates are cured at 180 °C and 7 bars for 120 min by means of a hot platen press, maintaining the laminate under vacuum conditions during the curing process. The laminate has an orthotropic linear elastic behaviour. The tensile modulus and strength in the fibres direction shown in Table 1, E_t and f_t, have been obtained from previous uniaxial tensile tests [9] following the standards [10]. The compressive modulus in the fibres direction E_c has been obtained from compressive uniaxial testing [11]. Nevertheless, proper final failures have not been achieved in the specimens submitted to uniaxial compressive loading, mainly due to problems related with the incorrect protection of the gripping surface. Thus, we have considered the value of the compressive strength in the fibres direction f_c given by [12] only as a reference. We would like to underline that this is only an illustrative value, because the material described in [12] has different fibre aerial weight than the composite here studied. The different stress–strain response in the fibres direction is clearly observed from the elastic properties listed in Table 1.

Parallelepiped specimens of length l, thickness h and width b (Fig. 1a) have been machined from plates composed of 5 and 8 plies. Therefore, two different thicknesses have been tested in order to analyse both flexural and shear failure modes. Note that, from the previous definition, the samples have a rectangular cross section of base b and height h. The experiments have been performed by means of a testing machine applying a central load at a constant rate of 1 mm/min till the failure of the specimen is produced. The displacement of the actuator is controlled in proportion to the signal of a loading cell. The applied load and the measurement of a KYOWA® strain gage bonded in the lower face of the central section of the specimen have been recorded (Fig. 1b). The three-point bending tool has been fabricated in stainless steel following the requirements established by the standards [2–5], with a support span L = 25 mm and a diameter of the fixed supports and the loading nose of 3 mm.

Observations for evaluating the location of the failure regions have been carried out by optical microscopy using a LEICA DR IRM microscope. Detailed images of the damage produced in the x–y plane have been made applying a magnification x50. The x–y plane has been chosen for examination due to its flat surface and higher visibility of the damage produced by flexural testing. Specimens for microscopy analysis have been illuminated with a monochromatic light in order to minimize chromatic aberrations and the images have been recorded on standard of colour black and white.

Table 1
Material properties of the carbon fibre reinforced epoxy in the fibres direction.

E_t [GPa]	E_c [GPa]	f_t [MPa]	f_c [MPa]
174.4 ± 13.8	94.01 ± 4.46	2600.9 ± 121.5	1500.0[12]

3. Analytical predictions

The problem of a pinned–pinned beam with a span L, submitted to a central load P, is studied (Fig. 1a). The rectangular cross section of base b and height h is analysed taking into account the different material behaviour under tension and compression (Fig. 4a). E_t and E_c are the tensile and compressive moduli observed in the two different regions delimited by the neutral fibre (NF) due to the flexural testing. The mid-span section of the beam is the most loaded, with a bending moment $M_z = PL/4$ and a shear load $V_y = P/2$.

The Navier–Bernouilli bending theory of slender beams is applied under the assumption of small deflections, small strains and linear elastic behaviour of the material [13]. If a differential length of the beam dx is studied, after the flexural deformation the neutral fibre does not change its original length because it suffers zero deformation. The local curvature radius of the neutral fibre is named as ρ. Observing the similar triangles marked in Fig. 2 with a line pattern, the relation $\rho/(dx/2) = y/(\varepsilon dx/2)$ can be found. Then, the normal strain distribution in the section due to the bending moment can be expressed as $\varepsilon = y/\rho$.

The normal strain and stress distributions caused by M_z are plotted in Fig. 3a and b considering $E_t > E_c$ as it has been indicated by the results of uniaxial testing (Table 1). The neutral fibre is not centred in the mid-height of the section due to the different response of the material under tension and compression. The maximum normal tensile and compressive stresses are σ_t and σ_c and their correspondent maximum normal strains are ε_t and ε_c, respectively (see Fig. 3a and b). The resultant forces from the normal stress distribution over the regions submitted to tension and compression are named as F_t and F_c . No external axil force is applied on the section, so the total resultant force of the normal stress distribution is equal to zero. Then, using the horizontal force equilibrium, we can find the parameter n (see Eq. (1)) which relates the elastic moduli and the heights of the regions under tension t and compression c.

$$F_t = F_c; \quad \frac{(E_t t/\rho)(t)}{2} b = \frac{(E_c c/\rho)(c)}{2} b; \quad \frac{E_t}{E_c} = \left(\frac{c}{t}\right)^2 = n \tag{1}$$

Substituting the fact that $h = c + t$ in Eq. (1), the position of the neutral fibre can be calculated as $t = h/(1+\sqrt{n})$ and $c = h\sqrt{n}/(1+\sqrt{n})$. Taking into account the tensile and compressive moduli obtained previously from uniaxial testing (Table 1), our composite has in the fibres direction an average moduli ratio n = 1.85.

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