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In-plane shear failure properties of a chopped glass-reinforced polyester by means of traction–compression biaxial testing

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We perform traction–compression biaxial testing in a chopped glass-reinforced polyester, applying in-plane perpendicular tensile–compressive loads to cruciform specimens. The purpose is to evaluate if this technique is suitable to perform shear tests and determine the shear strength and the shear failure strain of the composite. The failure properties obtained experimentally from this technique are compared with the analytical predictions of the Maximum stress, Maximum strain, Tsai-Hill and Tsai-Wu failure theories and the numerical results obtained by means of the Finite Element Method. The analysis is developed taking into account the different behaviour of the material under tension and under compression.

1. Introduction

There is a big variety of testing methods for determining shear properties in composites [1,2]. In all the cases it is crucial to obtain an acceptable uniform shear stress state in the test specimen. The shear strength and the shear modulus are the main parameters that these techniques should determine. The well-known Iosipescu and V-notched rail shear tests are the most utilised because they reasonably reproduce pure uniform shear stress states and allow to determine both shear strength and shear stiffness.

This work is focused on planar tension–compression testing with composite cruciform specimens [3–15], in order to evaluate if it is suitable to develop shear testing. To the knowledge of the authors, this is the first attempt to determine the in-plane shear properties of a composite by means of this technique. The procedure consists in applying on the arms of the cruciform specimen in-plane quasi-static perpendicular loads [3–15] by means of a multiaxial loading installation. The sample is designed to develop measurable homogeneous stress states in the intersection between its arms [4]. In this tapered central region the highest levels of stress are achieved and, so that, the failure of the material is produced due to the in-plane traction–compression stress state developed in the loading directions. The loading axes are the principal stress directions, because only normal stress components are developed. If these normal components are equal, the traction–compression biaxial stress state is equivalent to a pure shear stress state on the planes oriented 45° with respect to the orthogonal loading axes.

This physical principle has been already used by [16] to develop in-plane shear testing with both isotropic and orthotropic materials. The research was developed by means of a rectangular tensile coupon containing slots along the longitudinal axis, parallel to the tensile loading direction. Then the specimen was simultaneously subjected to tensile loading in the axial direction and to compression on its edges, in the perpendicular direction. Nevertheless, this technique has not been used a posteriori by any other investigator due to the complexity of the set-up and the difficulty of obtaining uniform stress fields [1,2]. Thus, very little data are available for evaluating if this principle is valid for developing shear testing and more studies are required.

In this investigation the analysed material is a brittle chopped-glass reinforced polyester whose behaviour is linear and quasi-isotropic, but different under tension and under compression [17]. This implies that the elastic tensile properties are different from the compressive elastic properties. Tasks as the shear strength, the shear failure strain and the shear modulus are estimated from the biaxial testing results. The experimental observables are the strain data acquired by means of strain gages situated in the biaxial loaded central zone of the specimen. Then, under tension–compression loading, the measured strains are transformed into stresses using the plane stress constitutive laws for an orthotropic material due to its different response under tension and compression.

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Few works have been dedicated to develop shear testing on polyester resins containing glass fibres in the form of chopped strand mat. At the time of this writing the authors are aware of different studies which determine the interlaminate shear strength in analogous composites [18–20], but not the in-plane shear properties. Therefore, numerical simulations by means of the Finite Element Method have been developed to evaluate the accuracy of the experimental results. Besides, the shear strength and the shear failure strain calculated from the experimental data are contrasted with the Maximum stress, Maximum strain, Tsai-Hill and Tsai-Wu failure analytical estimations [21].

The organisation of the paper is the following. Section 1 introduces the outline of the work. Section 2 describes the material, the geometry of the specimen, the test facility and the numerical model utilised. Section 3 explains the procedure followed to obtain from the strains acquired experimentally the failure shear properties and it shows the analytical predictions of the different orthotropic failure models studied. Section 4 presents the analysis of the experimental data and the comparison with the analytical and the numerical results. Finally, Section 5 gives the conclusions of the work.

2. Material, specimen, test facility and numerical model

A glass-reinforced polyester, with the glass fibres randomly distributed in the matrix, is studied. This composite is produced by means of a hand lay-up process. It is composed of a polyester resin with improved behaviour against fire, reinforced by 30.5% by weight of medium size chopped glass strands bonded together in mat. It is used in different applications in the automotive industry because, compared to other materials with equivalent strength, it is light and moisture-resistant. The material is fragile and it has an elastic linear behaviour. Tensile and compressive uniaxial tests have been developed in order to determine the elastic properties of the material under both loading cases. The different elastic properties under tension and compression [17] in any material direction are shown in Table 1, together with the failure stresses and strains. E_t and E_c are the tensile and compressive elastic modulus; ν_t and ν_c are the Poisson coefficients observed in the tension and compression uniaxial tests; σ_t and σ_c are the tensile and compressive strengths and their correspondent strains ε_t and ε_c, respectively. The average experimental values are shown in Table 1, which present a relative error that varies between 3% and 11%. The relation between the tensile and compressive elastic properties is similar to the response of a material with orthotropic behaviour $E_t/\nu_t = E_c/\nu_c$. This can be observed in Fig. 1, which shows as an example the results obtained from an uniaxial tensile test. The slope of the curve applied-stress versus strain in perpendicular to the loading direction is equal to -28 ± 3 GPa and corresponds to the relation $-E_t/\nu_t$. An equivalent response has been found in the uniaxial compressive tests.

In order to determine the shear properties of the material, biaxial testing has been developed by means of the cruciform specimen shown in Fig. 2, named as Geometry A–tc. The coordinate system x–y–z aligned with the two arms of the sample is also represented in Fig. 2. The specimen has the same dimensions as the geometry A proposed in [3], but the y-arm has been shortened from 160 to 60 mm in order to submit it to a compressive force and avoid as far as possible buckling during the experiments. Both arms have the same cross section and it is designed for applying the same level of loads on both arms of the specimen but with different sign (1/−1 loading case). This means that the same level of stress is applied on the two perpendicular axes for obtaining adequate failure modes [3–5]. We consider good failure modes those which are produced, due to the pure biaxial stress state, in the tapered central region of the specimen.

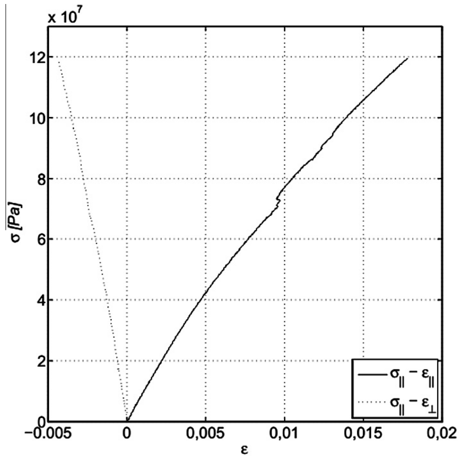

Fig. 1. Example of the stress–strain evolution of an uniaxial tensile test. Continuous line: stress in the loading direction versus strain in the loading direction. Dashed line: stress in the loading direction versus strain in perpendicular to the loading direction.

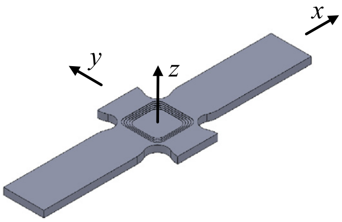

Fig. 2. Geometry A–tc. coordinate system x–y–z aligned with the two arms of the specimen.

Table 1
Material properties of the chopped glass-reinforced polyester. Different behaviour under tension and compression.

E_t (GPa)	ν_t	σ_t (MPa)	ε_t
7.0 ± 0.8	0.25 ± 0.03	123.0 ± 5.4	0.0176 ± 0.0009
E_c (GPa)	ν_c	σ_c (MPa)	ε_c
8.4 ± 0.3	0.30 ± 0.01	−73.1 ± 2.4	−0.0087 ± 0.0004

Tension–compression experiments are performed by means of a triaxial machine [3,4]. The four actuators placed in the horizontal plane of the machine apply in the two perpendicular arms of the specimen simultaneously equal tension and compression loading. The force sensors are monitored and the signals of a gage rosette, bonded in the region where the two arms of the specimen intersect, are acquired by means of a data recorder PCD-300B from KYOWA™.

The finite element code ABAQUS™ [22] is used to analyse the biaxial tension–compression loading problem. Linear-static analyses have been done and the numerical results are contrasted with the experimental data in order to review the validity of the tests results. A 2D plane stress model has been used, studying 1/4 of the specimen due to the bisymmetry of the problem with respect to the x and y axes. A reduced integration 4-node linear element is used. It has two degrees of freedom per node, which are the longitudinal displacements contained on the working plane. Under a tension–compression stress state it has been considered that the material develops a linear orthotropic behaviour. A study of the sensitivity to the element size has been performed until the results