Materials and Design 67 (2015) 344–353

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Quasi-static behaviour and damage assessment of flax/epoxy composites

Shaoxiong Liang [a,b,*], Papa-Birame Gning [a], Laurent Guillaumat [b]

[a] DRIVE–ISAT, Université de Bourgogne, 58027 Nevers Cedex, France
[b] LAMPA, Arts et Métiers ParisTech, 49100 Angers Cedex, France

ARTICLE INFO

Article history:
Received 13 September 2014
Accepted 27 November 2014
Available online 4 December 2014

Keywords:
Flax fibres
E-glass fibres
Polymer-matrix composites
Mechanical properties
Damage mechanics

ABSTRACT

Experimental investigations were conducted on flax and E-glass fibres reinforced epoxy matrix composites subjected to quasi-static loadings. Flax/epoxy samples having $[0]_{12}$, $[90]_{12}$, $[0/90]_{3S}$ and $[\pm45]_{3S}$ stacking sequences, with a fibre volume fraction of 43% have been tested under tension, compression and in-plane shear loadings. Overall, the compression strength of glass/epoxy was 76% greater than for the flax/epoxy composite. The damage evolution of flax/epoxy of $[0/90]_{3S}$ and $[\pm45]_{3S}$ samples has been evaluated in terms of transverse crack densities with respect to the load increment. The crack density exhibited a classical "S" shaped pattern for $[0/90]_{3S}$ and linearly for $[\pm45]_{3S}$ specimens versus the applied load. The final crack densities were respectively of 32/cm and 25/cm for the $[0/90]_{3S}$ and $[\pm45]_{3S}$ samples.

1. Introduction

With the environmental concerns, vegetal fibre reinforced polymer composites are increasingly considered as valid alternatives to conventional glass composites for mass production of composite materials [1]. Natural fibres offer various advantages compared to conventional man-made fibres and their processing requires low energy consumption and production costs [2]. Fibres are extracted from renewable and biodegradable resources and some varieties can offer specific properties, comparable to those of glass fibre. In particular, flax fibres extracted from an abundant and local resource in Europe, are known to have interesting mechanical properties as mentioned in the literature [3,4]. It emerged from the review that most of the available mechanical properties involving continuous Flax Fibre Reinforced Polymer (FFRP) composites are often limited to tensile data on unidirectional (UD) laminates loaded along the fibre direction [5,7]. However, most composite structures have multidirectional stacking sequences, and their compression and shear properties also need to be known. Therefore, the present work deals with the characterization of the quasi-static tensile, compression and in-plane shear properties of flax/epoxy. Several stacking sequences have been investigated: $[0]_{12}$, $[90]_{12}$ and $[0/90]_{3S}$, respectively noticed as FE_0, FE_90 and FE_090 specimens. Flax laminate of $[\pm45]_{3S}$, (FE_45), was dedicated to characterise the in-plane shear properties. The properties of FE_090 and FE_45 have been compared to E-glass fibre reinforced epoxy (GE) composites having similar stacking sequence (noticed GE_090 and GE_45) and fibre volume fraction.

Damage assessment is an important issue in the performance of composite materials. The different damage mechanisms occurring for general Synthetic Fibre Reinforced Polymer (SFRP) specimens subjected to tensile loading are well-identified, i.e. fibre breakage, matrix crack, fibre/matrix interfacial debonding and delamination [17]. Recently developed FFRP present similar damage mechanisms. Liu and Hughes [18] have investigated the fracture toughness of flax fabric reinforced epoxy composites. The main failure modes observed were debonding of fibres from the matrix and brittle fracture of matrix. Nevertheless, the most common damage causing stiffness decrease for cross-ply laminates in tension load was the intra-laminar transverse matrix cracking occurring in 90° layers [19]. For examples, authors [20,21] have measured an average crack density (CD) of 7–38/cm for glass fibre reinforced composite, whereas Ogihara et al. [22] measured 3 to 20/cm for carbon/epoxy layers having different stacking orientations. As to FFRP, our previous studies [9] have highlighted that the crack density exhibits a two-stage and three-stage evolution as a function of the life ratio for $[0/90]_{3S}$, and $[\pm45]_{3S}$, respectively.

In the present study, monotonic tensile loading up to failure and interrupted tensile test up to certain loading levels have been investigated in $[0/90]_{3S}$ and $[\pm45]_{3S}$ flax/epoxy (FE) specimens. Material degradation modes and damage evolution have been assessed by observation of the fractured edges under a Scanning Electron Microscope (SEM) and the internal crack using an Optical Microscope (OM).

---

* Corresponding author at: LAMPA, Arts et Métiers ParisTech, 49100 Angers Cedex, France. Tel.: +33 2 41 20 73 59.

E-mail address: shaoxiong.liang@ensam.eu (S. Liang).

http://dx.doi.org/10.1016/j.matdes.2014.11.048
0261-3069/

Table 1
Properties of flax/epoxy and glass/epoxy composites. Standard deviations are given in brackets.

Notation	Fibre	Fabric	m_{area} (g/m^2)	Stacking sequence	V_f (%)	V_p (%)	ρ_c (kg/m^3)	t (mm)
FE_0	Hermès	UD	140 (6)	$[0]_{12}$	43.9	0.48	1310 (10)	2.55
FE_90	flax			$[90]_{12}$	(1.5)	(0.02)		(0.12)
FE_090		Non-	235 (16)	$[0/90]_{3S}$	43.1	3.1	1280 (10)	2.18
FE_45		crimp		$[\pm 45]_{3S}$	(0.6)	(0.3)		(0.07)
GE_090	E-glass	Non-	430 (5)	$[0/90]_{3S}$	42.5	5.9	1730 (30)	2.33
GE_45		crimp		$[\pm 45]_{3S}$	(1.0)	(2.2)		(0.04)

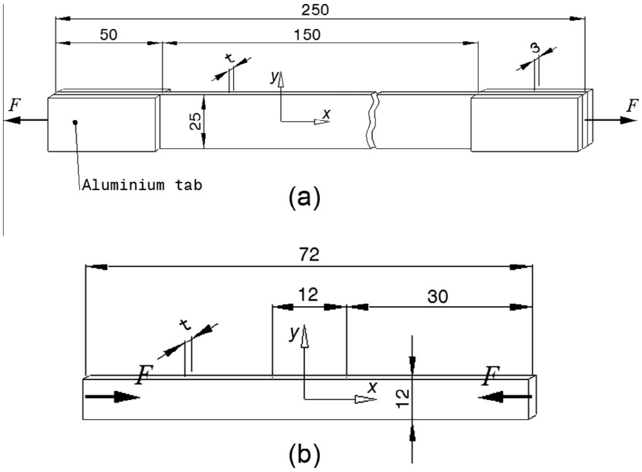

Fig. 1. Geometry of (a) tensile and in-plane shear and (b) compression specimens. Dimensions are given in mm.

2. Experimental methods

2.1. Materials

Flax/epoxy (FE) and E-glass/epoxy (GE) composites were made from dry reels of UD or balanced non-crimp fabrics. All fabrics were used as received without any further treatment. Composite layers were hand-laid up after being impregnated with an epoxy matrix system SR 8200/SD 8205 supplied by Sicomin. The matrix density was of 1.14 kg/m^3 at 20 °C and the measured glass transition temperature (T_g) was 88 °C [6]. Laminates were cured under pressure between two heating plates. The temperature was constant at 60 °C for 8 h. The exhaustive parameters of the constituents and the fabrication process are given in [8,9]. The composite plates were then cut with a high-speed abrasive disc. Specimen notation, stacking sequences, fibre (V_f) and porosity (V_p) volume fractions, densities (ρ_c) and thicknesses (t) are given in Table 1. Comparable V_f of around 43% were measured for all composite types according the Method II of the standard ASTM: D 3171-11. This method consists of measuring the reinforcement quantity in the composite materials and the final composite thickness (t in mm). The fibre mass is calculated by the dry fabric areal weight (m_{area} in g/m^2) multiplied by the number of plies (n). The fibre volume fraction is calculated by Eq. (1). Where ρ_f is the fibre density and equal to 1500 kg/m^3 for flax fibre and 2600 kg/m^3 for glass ones.

$$V_f = \frac{n \times m_{area}}{\rho_f \times t} \qquad (1)$$

2.2. Specimens and experimental measurements

The tensile properties of all specimens have been determined by quasi-static tests according to ISO 527-4 [23] standard on

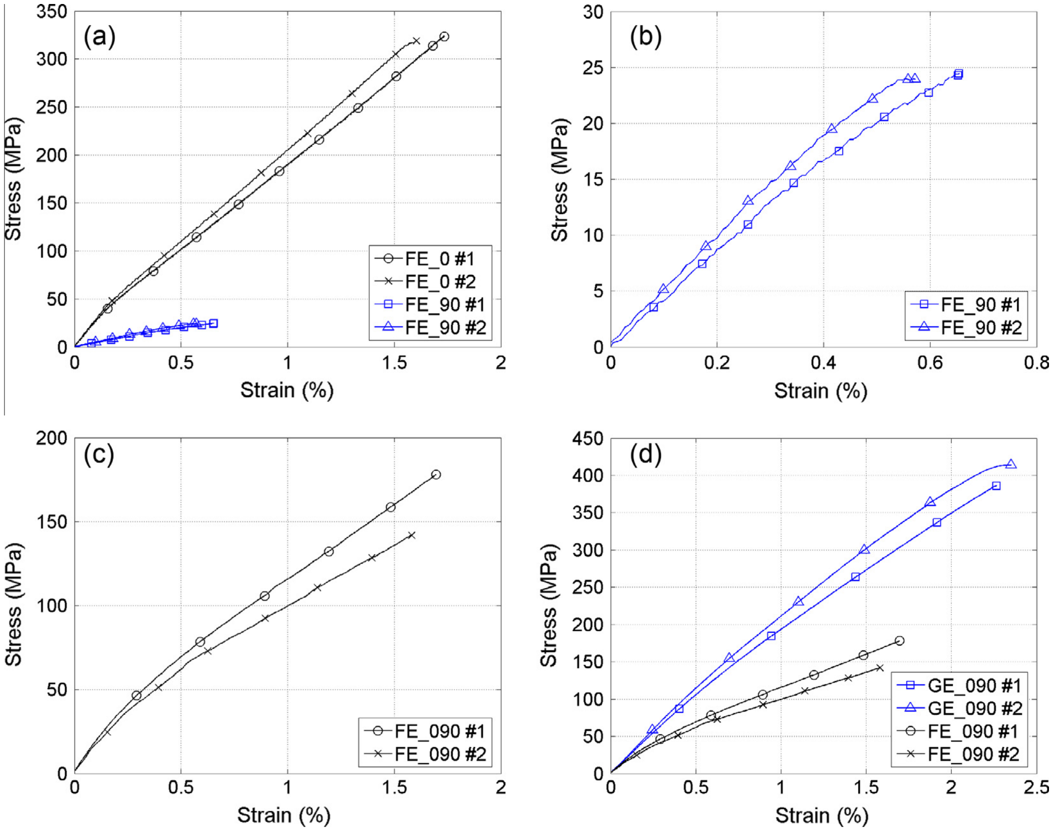

Fig. 2. Typical tensile stress–strain curves of (a) FE_0, (b) FE_90, (c) FE_090 and (d) GE_090 specimens.