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Mechanical behaviour of plain-knit reinforced injected composites: Effect of inlay yarns and fibre type

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ABSTRACT

This paper investigates the effect of inlay yarns and fibre type (E-glass, basalt, carbon) to improve the mechanical behaviour of plain knit reinforced composites (epoxy matrix). The tensile behaviour of the dry reinforcement was investigated in the wale and course-directions and has shown that the course-wise deformation is drastically reduced whereas the strength is strongly increased when inlay yarns are included. Fibre type has a weak effect on deformation and strength. For the composite material, processed by Liquid Composite Moulding, the carbon fibre reinforcement gives always the best results whatever the testing direction. Inlay yarns decrease the 0° mechanical properties, whereas 45° and 90° are increased. Moreover a quasi-isotropic behaviour is obtained when using two inlay yarns, irrespective of the fibre types.

1. Introduction

Fibre reinforced composite materials are increasingly used in industrial applications requiring high specific mechanical properties. They cover a large range of mechanical and physical properties due to the numerous parameters involved in their manufacturing. Amongst them, the fibre arrangement in the matrix has an important effect on the mechanical properties of the composite. Up to now, woven and unidirectional reinforcements are mainly used in industrial applications. The low curvature of the fibres confers high performance to the composite. However, issues related to fibrous architecture remain, especially for composite forming. Complex shape parts manufacturing requires cutting and assembly operations, resulting in material wastage and high production costs. This leads also to a local weakening in assembly areas, mainly related to the reinforcement discontinuity. Therefore new reinforcement architectures were designed, and, amongst them, knitted fabrics meet the technical requirements for complex shapes forming. This technology enables the development of net-shape fabrics, including holed preforms. Knits are obtained by intermeshing loops of fibre yarns resulting in a high deformation ability compared with woven fabrics [1,2] thanks to the possibility to change the shape of the loops [3,4]. This deformation ability is especially suitable for stretch forming and deep drawing, since it allows to distribute homogeneously the textile deformation, avoiding local material heterogeneities in a single part [5,6]. A low strain energy is required allowing wrinkles to appear lately in comparison to woven fabrics [7,8]. Excellent properties for composite moulding are obtained, especially for stacking.

Knit reinforced composites exhibit also interesting impact behaviour properties. Stitches of adjacent layers overlap each other, reducing inter-laminar resin-rich areas and crack propagation. The inter-laminar fracture toughness is then increased comparing to woven and UD composites [9–12]. Indeed the delamination of knit composites involves both mode I and mode III crack propagation [12]. Compression-After-Impact tests highlight the high damage tolerance of knitted composites: they exhibit a relative compressive strength retention higher than woven composites [9].

However, knitted composites exhibit low in-plane mechanical properties, close to short fibres composites, because of the curvature of the fibres [13,14]. The compressive properties are isotropic and depend strongly on the matrix properties [15]. On the contrary, the tensile properties are anisotropic and related to the reinforcement. Up to now, most studies were focused on basic knitted structures such as plain, 1 × 1 rib and Milano made of glass fibres. These investigations highlighted that the composite properties depend on knit architecture [16,17] and on knit geometrical parameters such as stitch size, stitch density and yarn length [16,18]. An initial fabric deformation before composite processing leads to an improvement of the properties in the stretched direction and to a loss of properties in the transverse direction [19]. However biaxial stretching before composite forming has a negligible effect [20]. It is then demonstrated that an improvement of the tensile properties would require a modification of the fibre distribution in the

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material. No studies on the effect of the fibre type on the knitted composite behaviour are known.

In this paper, the effects of knit construction and fibre type on the composite tensile behaviour are investigated. Previous works [21,22] were focused on the two basic knitted reinforcements, plain and 1 × 1 rib. This latter is made up of front and back stitches, leading to a three-dimensional structure and a higher deformability is then achieved than with plain-knit, only made up of front stitches. Plain structure confers the best tensile properties to the composite, especially in the wale-direction, due to a less isotropic fibre orientation distribution, and has been chosen as the starting point of the optimisation aiming to improve the composite mechanical properties [23–25]. Plain-knit composites are anisotropic with higher properties in the wale-direction. These reinforcements have higher deformation ability in the course-direction. A correlation between fabric deformation ability and composite properties was carried out. The optimisation of the plain-knit architecture requires to reinforce the course-direction and to find a compromise with the deformation ability (reinforcing means adding straight yarns, what obviously decreases the extensibility). The knitting process allows to add non-knitted yarns in the course-direction into the fabric, thanks to inlay yarns obtained by two techniques: float loops [26] or tuck loops [26,27]. In this paper, the cross effects of inlay yarns, their number, and the fibre type on knitted fabric deformability and composite mechanical behaviour are investigated.

2. Materials and process

2.1. Fibres and resin

E-glass, basalt and carbon fibres are studied to highlight the effect of the fibre type on the behaviour of the fabric and the composite. Glass and carbon fibres are the most widely used in the composite manufacturing industry. The former are mostly dedicated to mass production materials due to its excellent price-quality ratio and the latter provide high cost structural materials, with excellent mechanical properties. Basalt fibres, considered as emergent, have interesting physicochemical properties and slightly better mechanical properties than glass fibres.

The yarn diameter is a key parameter of a knit, it controls the jamming of the loops [21]. In order to produce equivalent knitted fabrics, roving bobbins with a similar yarn diameter were chosen. This diameter is calculated from diameter and number of filaments by considering a hexagonal fibre packing. Fibres and roving properties are given in Table 1. Glass and basalt fibres have similar properties and both rovings have the same linear density. However a smaller filament diameter confers to basalt yarns a lower bending stiffness. Carbon fibres have thinner filaments and exhibit a higher Young's modulus and a lower density, that confer to the yarns lower bending stiffness and linear density.

The resin used is a two components epoxy system (SICOMIN SR 1710 resin with SD 8822 hardener) designed for resin transfer moulding processes. This system is characterized by a very low viscosity and high mechanical properties, conferring a high inter-laminar shear strength to the composite (Table 1).

2.2. Knitted fabrics

Knitting consists in intermeshing loops of yarns to produce fabrics from a single or from several yarns. Weft-knitting refers to the knitting direction: the stitches are knitted successively in the weft-direction, also called course-direction. The loops are interconnected in the wale direction called also columns. Plain-knit, only made of front stitches, is the basic architecture (Fig. 1) in which inlay yarns were added to reinforce the course-direction. Every four plain stitches, inlay yarns are linked to the knit by tuck stitches (Fig. 2). Between two consecutive tuck stitches, the inlay yarn forms a float loop. Basic plain-knit (*P*0) and plain-knits with one (*P*1), two (*P*2) and three (*P*3) inlay yarns per course were manufactured and are presented in Figs. 1 and 2.

All knits under study were produced from each fibre type with the same knitting parameters in order to get equivalent stitch sizes, given by the geometrical parameters defined in Fig. 1. W, C and L_Y are respectively the average wale width, course height and yarn length per stitch. W and C were calculated from fabric dimensions and number of stitches, whereas L_Y is calculated from fabric weight and yarn linear density. The mean values calculated for all knits under study are $W = 4.2 \pm 0.4$ mm, $C = 2.5 \pm 0.1$ mm and $L_Y = 17.5 \pm 3.9$ mm. The important dispersion of these parameters (5–20%) is related to the properties of the different fibres. The stitch size depends on knitting parameters but also on the loop

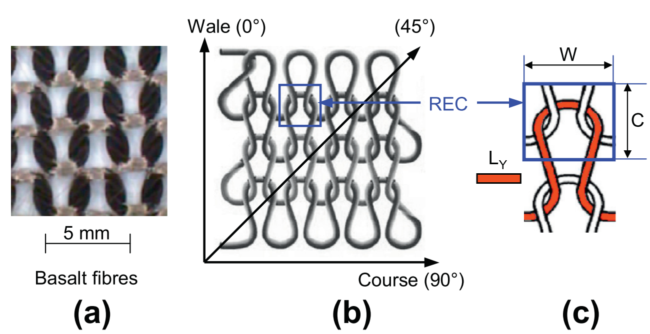

Fig. 1. Plain-knit basic architecture (*P*0): (a) photograph of a basalt fabric; (b) testing directions and (c) representative elementary cell (REC) and geometrical characteristics of the loop.

Table 1
Fibre, yarn and resin properties.

Fibre type	E-glass	Basalt	Carbon	Resin type	
	Owens corning Vetrotex T30 111AX23	Basaltex BCF	Tohotenax HTA 5131 6 K Z10	Thermoset epoxy resin SICOMIN SR1710 + SD8822 hardener	
Fibre properties				Tensile properties	
Filament diameter	16 μm	13 μm	7 μm	Young's modulus	3680 MPa
Fibre density	2620 kg m^{-3}	2700 kg m^{-3}	1760 kg m^{-3}	Rupture stress	85 MPa
Young's modulus	80 GPa	84 GPa	238 GPa	Strain at break	3.1%
Yarn properties				Bending properties	
Number of filaments	1200	1672	6000	Modulus	3720 MPa
Yarn diameter	0.58 mm	0.56 mm	0.57 mm	Maximal stress	136 MPa
Linear density (Dy)	600 tex	600 tex	400 tex	Strain at break	5.20%
Bending stiffness	0.31 N mm^2	0.20 N mm^2	0.16 N mm^2		