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MODELLING AND SIMULATION OF THE MECHANICAL BEHAVIOUR OF WEFT-KNITTED FABRICS FOR TECHNICAL APPLICATIONS

Part I: General considerations and experimental analyses

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Abstract

This paper is in four parts. The first is related to general considerations and experimental analyses, and each of the successive papers is related to different approaches to theoretical analyses of the mechanical behaviour of weft-knitted fabrics and weft-knitted reinforced composites made of glass fibre. The objective is to find ways of improving the mechanical properties and simulating the mechanical behaviour of knitted fabrics and knitted reinforced composites, so that the engineering design of such materials and structures may be improved.

In Part I, general considerations, experimental analyses and ways of improving the mechanical properties of weft-knitted fabrics and knitted reinforced composites are discussed.

In Part II the first model is presented, a 3D model based on the classic elastica theory, and it is used to calculate the load-extension curves of a plain weft-knitted fabric in coursewise and walewise directions. Good agreement is obtained between theoretical and experimental results.

In Part III the second model is presented, a 2D model based on FEA (finite element analyses). A plain weft knitted fabric, based on the simple loop structure, is simplified and represented by a 2D hexagonal structure constructed by non-linear truss elements. The characteristics of the truss elements for FEA simulation are obtained from experimental results through an analytical method when a loop is converted to a FEA model. The elongation deformation is simulated in one, two and many directions. The model can also be used to calculate a planar knitted fabric to be deformed to fit a 3D spherical mould.

In Part IV the technologies for the development of weft-knitted 3D complex shape preforms] are surveyed and a third model is presented, a 3D model based on FEA (finite element analyses). A solid representation of a 2D yarn is built up, and a MES (mechanical event simulation) is applied to obtain a 3D shaped loop. The final knitted fabric geometry is obtained by interacting this loop with the adjacent loops, according to the dimensional properties of the knitted fabrics and by using a MES. Finally, the geometry of the reinforcement inside the composite is built up, and the composite material is divided into small tetrahedric elements to obtain a mesh of finite tetrahedric elements (FEA). The average values of the mechanical properties are obtained with FEA and compared with the experimental ones.

Keywords:

Knitted fabric, load-extension curve, technical textiles, modelling, mechanical properties, composite materials

1. INTRODUCTION

The application of fibrous materials in the reinforcement of matrices made from polymers is a very interesting field both from the research and industrial points of view. The importance of these materials, known as composite materials, is increasing in the replacement of monolithic materials such

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as metals. In this case, composite materials present various advantages such as high specific mechanical properties, due to their low weight, and good heat & corrosion resistance.

The need to design materials with different properties in each direction and to reinforce the thickness direction in order to overcome delamination has made textile technologies very attractive for the production of composite reinforcements. Weaving technology can produce different fabric types, from planar to multi-layer and integral profile fabrics. Braiding technology is suitable for the production of tubular preforms from single to multi-layer, presenting high formability and superior mechanical behaviour. Warp knitting technology can be mainly used for the production of fabrics reinforced by non-crimp yarns inlaid according to the requirements of the application. Flat knitting technology is mostly suited to producing complex shaped fabrics and sandwich fabrics. Figure 1 shows some examples of these.

Figure 1. Examples of the versatility of weft knitting technology for the production of 3D complex shaped fabrics for composite reinforcement

The use of weft-knitted fabrics in composite reinforcements is limited, due to their poor mechanical properties. The tensile behaviour of weft-knitted fabrics is strongly restricted by its loop formation. During the application of a tensile load, the loops change their shape in order to accommodate the applied load. In this part of the deformation, small loads lead to large displacements, which is the typical behaviour of a low stiffness material. However, due to this behaviour, knitted fabrics are particularly suitable for applications where resistance to impact and absorption of energy are the main requirements.

In a recent issue of the Lufthansa Magazine [1], dedicated to the celebrations of 100 years of flight since the Wright brothers, there is an enlightening article concerning the next generations of commercial aircraft, which will use a method for producing entire fuselage sections by placing woven, knitted and sewn structures of carbon-fibre in a mould into which casting resin is then poured and baked. These CFRPs (carbon-fibre reinforced plastics) will enable the next generation of aircraft to consume 20% less fuel, and the subsequent generation to consume 30% less.

Weft-knitting is the most suitable technique for the production of 3D fabrics for complex shape composite reinforcements. However, due to the their loop structure, weft-knitted preforms exhibit poor tensile properties, which limit their range of application in areas where resistance to impact is the dominant feature. This paper discusses ways in which stiffness could be improved and describes the experimental work done at the University of Minho regarding the improvement of the mechanical properties of composite materials reinforced by weft-knitted glass fabrics. The effects of the fibre orientation are analysed by comparing the tensile testing results obtained for different glass weft-knitted structures, i.e., single jersey, 1x1 jersey and fleece. These weft-knitted structures have been used in the reinforcement of a polyester resin matrix. The composite materials thus obtained have been tested in order to analyse the effects of four different factors on the tensile properties: testing direction (courses or wales), number of layers (1 or 2), type of structure (jersey, 1x1 jersey and fleece) and pre-tensioning of the weft-knitted fabric structure (0% or 20%). The testing results are presented, and the effects of each factor on the tensile behaviour of composite materials reinforced by weft-knitted structures are discussed.

2. GENERAL CONSIDERATIONS

The mechanical properties of weft-knitted fabrics are strongly related to fabric structure, yarn properties and fabric direction. For a particular testing direction, the tensile behaviour of the fabric is highly non-linear, which makes the evaluation of material properties very difficult. In fact, a closer look and a careful examination of the loops' behaviour during testing can reveal a two-stage deformation process. Figure 2 presents a typical load-extension characteristic curve for a weft-knitted fabric tested in the walewise direction.

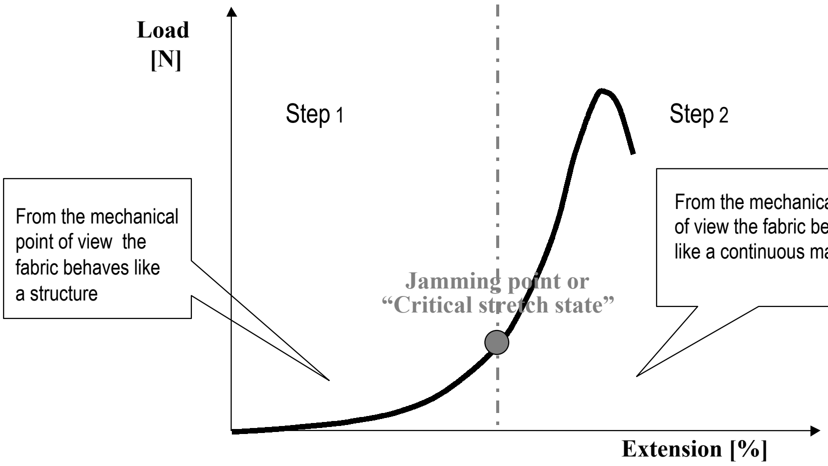


Figure 2. Typical load-extension characteristic curve for a weft-knitted fabric
Step 1: stretching of the curved yarns up to the critical stretch state, which is a virtual state where the yarns are straightened without yarn elongation itself;
Step 2: the elongation of the straightened yarn starts.

As can be seen in Figure 2, the deformation process can be divided into twostages. In the firststage, the deformation of the knitted fabric is due mainly to the straightening of the curved yarns. The yarns slip with friction in the interlacing regions, while the diameter of the yarn continuously decreases because of local compression effects. This process continues up to the 'critical stretch state' or 'jamming state', which is a hypothetical state of deformation. From the mechanical point of view, in this initial stage of deformation, the fabric behaves like a structure rather than a continuous material. The definition of Young's modulus for the structure encounters some theoretical barriers. As the deformation is non-linear, Hook's law cannot be verified, and so it is not possible to consider Young's modulus. As an alternative, the term stiffness or 'tensile rigidity' may be used to describe and compare the mechanical behaviour of different fabrics. This stiffness is related to the flexural rigidity of the yarn (G_0) that forms the loop, and as the loop length increases (and therefore the radius of curvature of bending the yarn (R) also increases), the bending moment or couple (B) decreases and vice versa, in order to keep the flexural rigidity of the yarn constant, so that, for the case of a circular yarn cross section to which a yarn may approximate:

$$G_0 = B \times R = \pi d^4 E / 64 \qquad (1)$$

where:

d = yarn diameter;
E = Young's modulus of yarn material;

The second step is characterised by the yarn deformation within the structure as the load is transferred directly to the yarn. When the load increases, the cross-section of the fabric becomes more compact. Although a small structural effect of the fabric still exists, this may be ignored as it is less important in the deformation process.

Some practical conclusions from the above are as follows:

- in order to increase the stiffness of knitted fabrics, and therefore their capacity to resist deformation from applied loads, pre-tensioning techniques or the introduction of straight yarns in various directions is required;
- in order to increase the resilience of knitted fabrics, and therefore their capacity to absorb energy, a relaxed stretchable loop structure is required.

This may be illustrated in Figure 3 below.

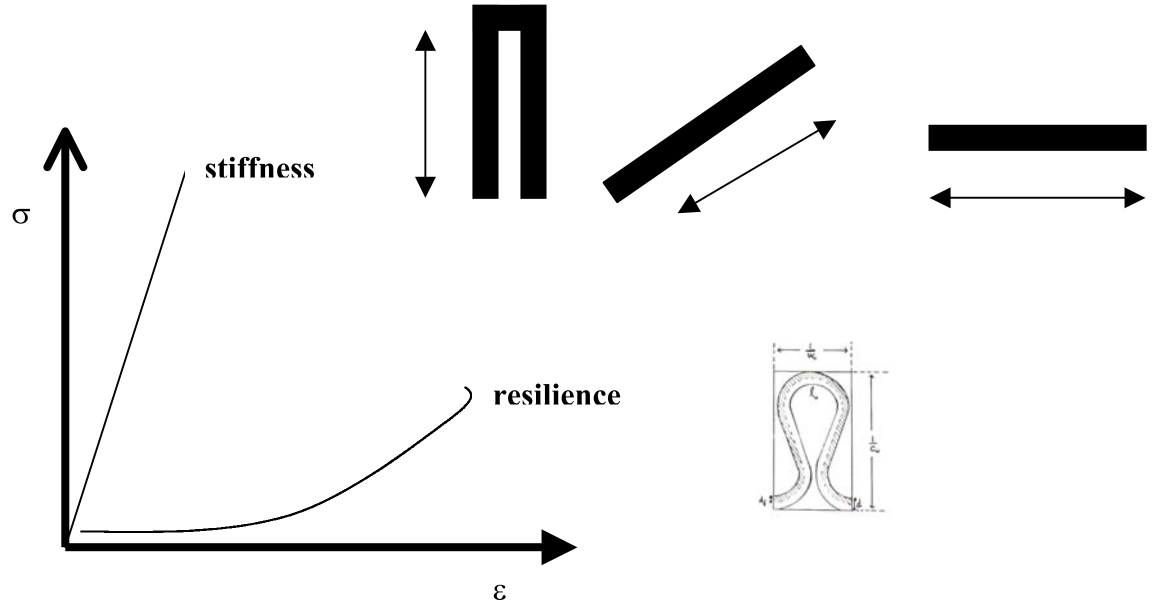


Figure 3. Designing the structure for particular properties

In this context it may be argued that in the future it will be possible to develop *smart or active structures* by using *memory shape fibres* so that by means of a triggering stimulus (i.e. temperature), the material could change from stiff to resilient and vice versa by straightening or buckling the yarns or fibres.

3. TENSILE PROPERTIES OF WEFT-KNITTED GLASS FIBRE FABRICS

3.1. Testing plan

In order to study the tensile properties of weft-knitted glass fibre fabrics for applications in the production of complex shaped preforms, four different fabric structures were selected:

- single jersey,
- 1x1 jersey,
- fleece,
- sandwich connected by yarns.

The testing of these structures was conducted in order to study the influence of fibre orientation in the coursewise direction on the mechanical performance of these fabrics. Table I presents the dimensional properties of these structures, while Figures 4 to 7 show their technical face and technical back.

Table1. Dimensional properties of the knitted structures selected

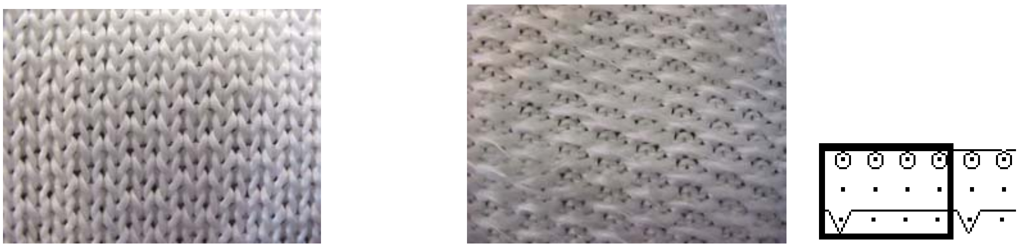
	Single jersey	1x1 Jersey	Fleece	Sandwich
Mass (g/m^2)	1100	1300	1350	3500
Loop length (cm)	0.925	1.97	2.72	0.836 and 0.724
Tightness factor	21.8	20.5	26.1	24.2
Courses/cm	6.4	3.2	2.5	4.15
Wales/cm	5.3	2.9	1.6	1.78
C/W (loop shape factor)	1.21	1.10	1.56	2.33

(a) (b) (c)

Figure 4. Single jersey
(a) Technical face (b) Technical back (c) Diagram

(a) (b) (c)

Figure 5. 1x1 jersey
(a) Technical face (b) Technical back (c) Diagram



(a) (b) (c)

Figure 6. Fleece
Technical face (b) Technical back (c) Diagram

(a) (b) (c)

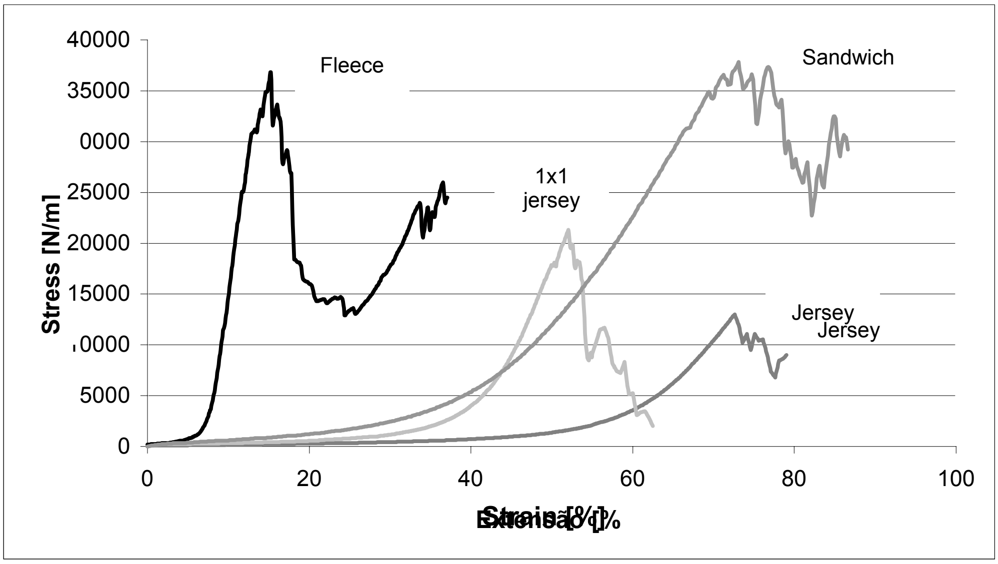
Figure 7. Sandwich
(a) Technical face and technical back (b) Cross-section (c) Diagram

3.2. Testing results

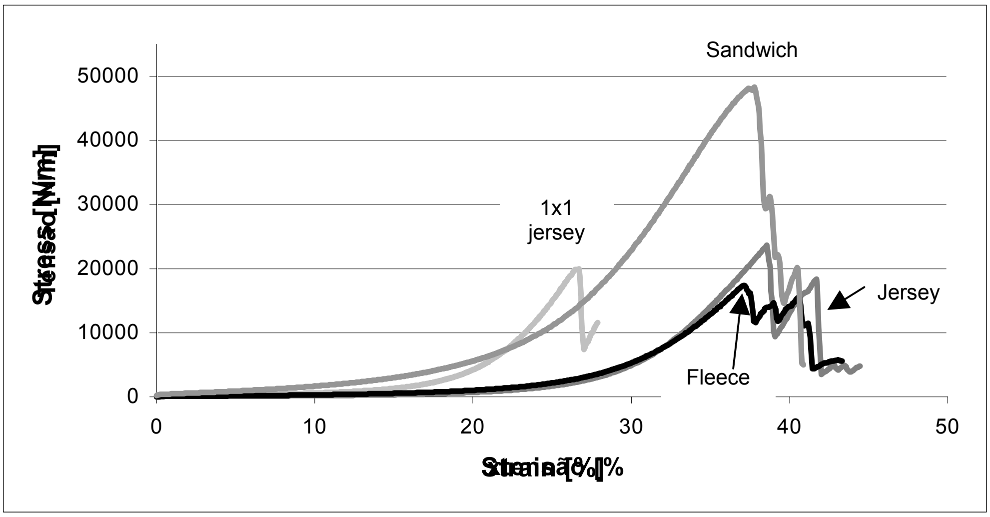
The testing of the knitted structures was conducted in both coursewise and walewise directions. Ten samples of each structure were prepared and tested in each direction using a Housfield H10KS universal tensile tester. The results obtained are presented in Table II, while the corresponding load-extension curves are shown in Figure 8.

Table 2. Tensile properties of the knitted fabrics selected

Structure	Direction	Tensile strength [N/m]	Extension to rupture [%]
SINGLE JERSEY	Wales	22080	37.98
	Courses	12630	71.88
1x1 JERSEY	Wales	22386	28.14
	Courses	19627	52.31
FLEECE	Wales	18568	37.07
	Courses	38007	16.36
SANDWICH	Wales	44460	38.46
	Courses	37680	68.99



(coursewise direction)



(walewise direction)

Figure 8. Load-extension curves for each knitted structure tested (1 layer; 0% pre-tension)

3.3. Results analysis and conclusions

Analysing Table 2 and Figure 8, it is possible to conclude that:

- the stiffness of weft-knitted fabrics is extremely low;
- the introduction of non-knitting yarns (fleece) significantly increases the breaking load of weft-knitted fabrics;
- the introduction of non-knitting yarns significantly decreases the breaking extension of weft-knitted fabrics;
- the introduction of non-knitting yarns in the coursewise direction does not affect the tensile properties in the walewise direction;
- the non-linear initial part of the load-extension curve, which is responsible for the low stiffness of weft-knitted structures, may be modified by the introduction of non-knitting yarns, thus increasing stiffness;
- the introduction of directional non-knitting yarns enables the control of fabric anisotropy.

Furthermore, by analysing the load-extension curves, it can be seen that the knitting yarn starts to show an excessively high extension under load, which could be a drawback for applications in composite materials. A strategy proposed to overcome or minimise this problem is pre-tensioning of the knitted fabrics before resin impregnation. The values of the pre-tension to apply in each case could be indicated by the load-extension curves. As an example, for the single jersey structure, a pre-tension of about 3750 N/m may be applied to eliminate 55% of the initial extension.

4. TENSILE PROPERTIES OF WEFT-KNITTED REINFORCED COMPOSITES

The weft-knitted fabrics tested before have been applied in the reinforcement of a polyester-unsaturated resin. The hand lay up technique was used to obtain composite materials with 30% of fibre volume fraction.

4.1. Testing plan

In order to evaluate the influence of various factors on the tensile properties of weft-knitted reinforced composites, experimental work has been undertaken using an Instron universal tensile tester, according to the ASTM D638 standard, at a speed of 2 mm/min, using a strain gauge. The factors considered are presented in Table 3.

Table 3. Factors considered for the analysis

Factors	Levels
Weft-knitted structure	single jersey / 1x1 jersey
Testing direction	Wales / Courses
Number of reinforcing layers	1 / 2
Reinforcement pre-tension level	0% / 20%

The tensile properties of composite materials reinforced by fleece and sandwich structures have also been evaluated. In the case of the fleece structure, the reinforcement has been set at an initial pre-tension level of 20%, and the composite materials tested in the coursewise direction only.

4.2. Deformation mode

Figure 9 shows the deformation mode of a composite material reinforced by a weft-knitted fabric during a uniaxial tensile test. Figure 9 (a) shows the initial phase of the load application, where no visible alteration of the sample is apparent. At the next stage, the resin starts cracking at several points of the material, thus producing characteristic sharp sounds (Step 2). The phase after that (Step 3) is characterised by the appearance of several cracks along the sample width, corresponding to resin-fibre debonding (Figure 9 (b)). Finally, fracture occurs due to rupture of the fibres which connect both edges of the crack (step 4).

(a) Step 1 & 2 (b) Step 3 (c) Step 4

Figure 9. Steps in the deformation of a weft-knitted reinforced composite

Analysing a typical load-extension curve of a weft-knitted reinforced composite (Figure 10), it can be seen that Step 1 corresponds to the initial part of the curve which is linear; Step 2, though not well defined in the curve, occurs between Step 1 and Step 3, corresponding to the part where the curve loses its linearity; Step 3 is perfectly visible in the curve due to the small oscillations which correspond to the opening of the cracks; Step 4 is illustrated by the vertical line dropping sharply at maximum strength.

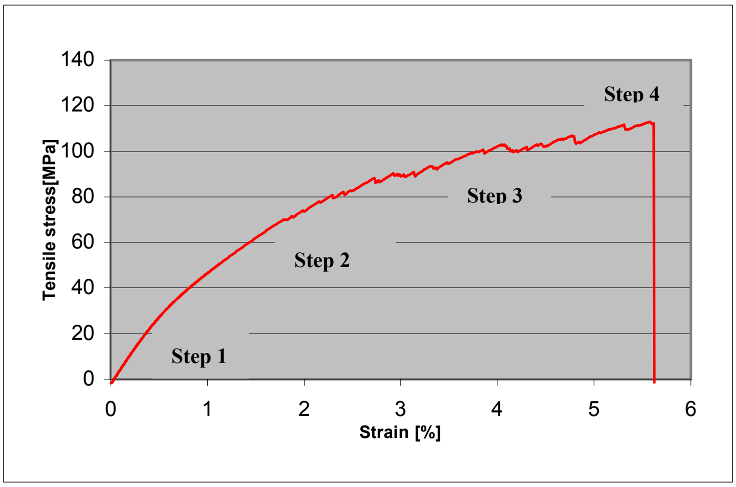


Figure 10. Steps of deformation of a weft-knitted reinforced composite by analysing the load-extension curve

4.3. Interaction reinforcement/resin/composite

Figures 11 to 14 present the load-extension curves for the resin, knitted fabrics and corresponding composite
materials.

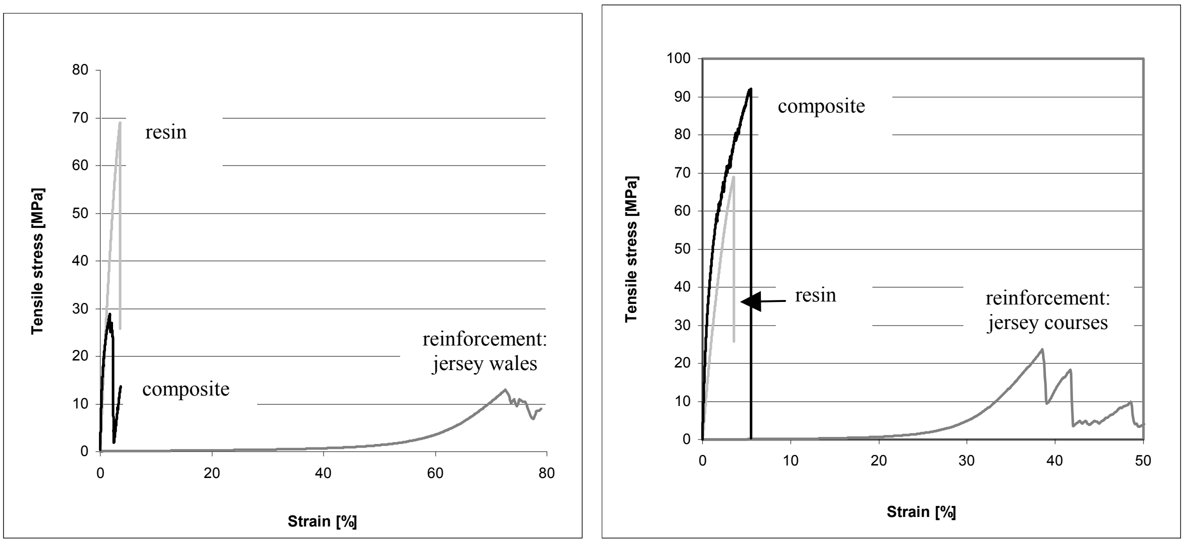


Figure 11. Tensile behaviour of resin, single jersey and corresponding composite material (1 layer; 0% pre-tension)

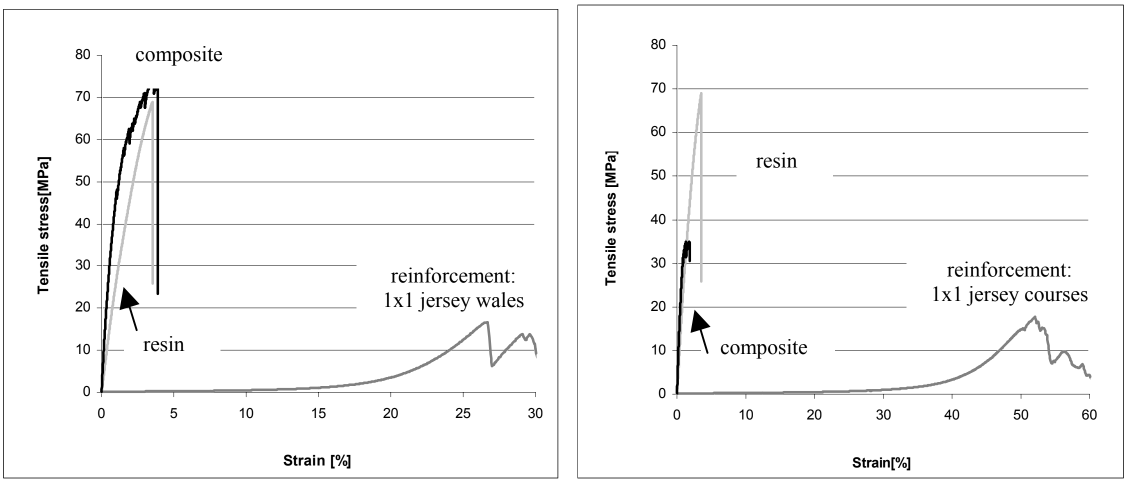


Figure 12. Tensile behaviour of resin, 1x1 jersey and corresponding composite material (1 layer; 0% pre-tension)

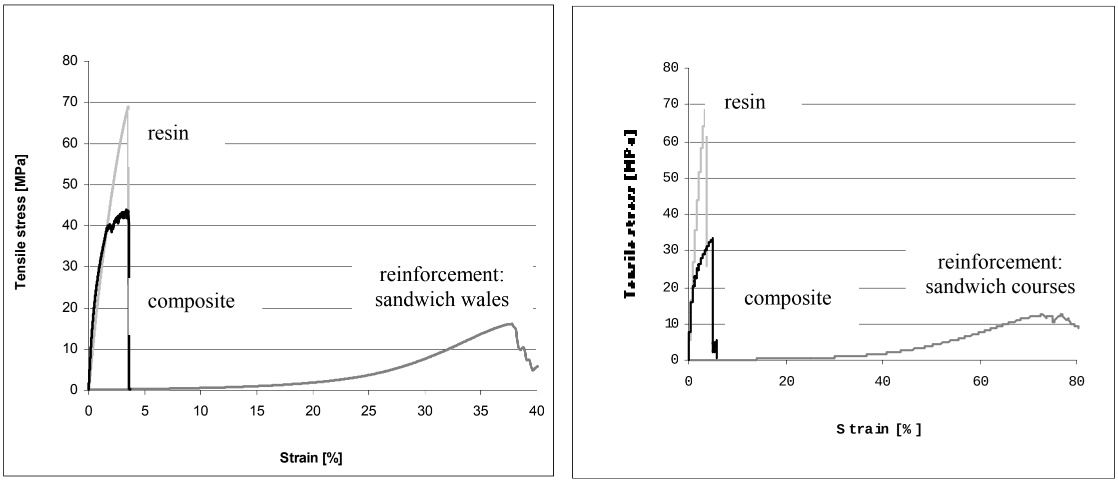


Figure 13. Tensile behaviour of resin, sandwich structure and corresponding composite material (1 layer; 0% pre-tension)

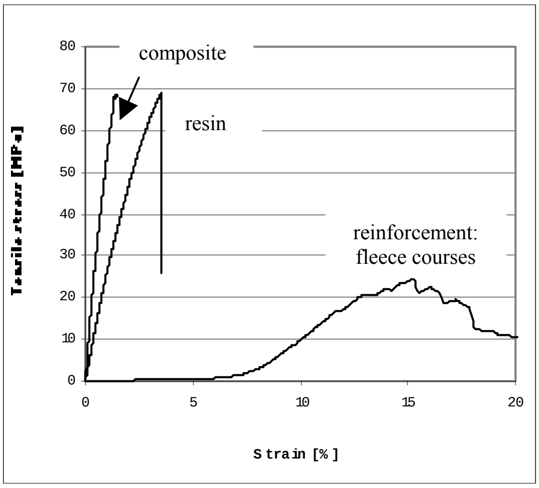


Figure 14. Tensile behaviours of resin, fleece structure and corresponding composite material (1 layer; maximum pre-tension: approx. 15%)

As can be seen, the interaction between the three curves presented in each diagram differs considerably from that of conventional composite materials. In a conventional composite material, the reinforcement alone presents better tensile performance than the composite itself, while the resin presents an intermediate performance. In this case, all the reinforcements present a worse tensile performance than the resin alone, while the correspondent composite materials present a better performance than both the reinforcements and the resin separate.

4.4. Testing results

Tables 4, 5 and 6 show the results obtained for maximum stress and strain and for Young´s modulus, respectively.

Table 4. Maximum strength for each composite material tested [MPa]

	Walewise direction				**Coursewise direction**			
	1 Layer		**2 Layers**		**1 Layer**		**2 Layers**	
	0%	**20%**	**0%**	**20%**	**0%**	**20%**	**0%**	**20%**
Jersey	85.14	100.44	76.29	108.77	24.98	35.52	28.77	36.02
1x1 Jersey	76.42	83.95	82.17	94.04	34.36	49.69	36.18	52.36
Fleece						77.93		65.22
Sandwich	36.75				25.44			

Table 5. Extension at maximum strength for each composite material tested [%]

	Walewise direction				**Coursewise direction**			
	1 Layer		**2 Layers**		**1 Layer**		**2 Layers**	
	0%	**20%**	**0%**	**20%**	**0%**	**20%**	**0%**	**20%**
Jersey	5.34	4.16	4.54	5.25	1.55	3.84	1.73	2.40
1x1 Jersey	4.14	5.48	5.24	5.96	1.76	2.87	1.79	3.98
Fleece						1.82		1.62
Sandwich	3.09				4.06			

Table 6. Young´s modulus for each composite material tested [MPa]

	Walewise direction				**Coursewise direction**			
	1 Layer		**2 Layers**		**1 Layer**		**2 Layers**	
	0%	**20%**	**0%**	**20%**	**0%**	**20%**	**0%**	**20%**
Jersey	6479.9	6562.1	4995.4	6314.5	3447.68	3811.56	3418.7	4050.1
1x1 Jersey	5690.1	6420.6	5736.6	6185.1	4089.64	5056.75	3997.7	5284.2
Fleece						7603.02		6163.8
Sandwich	4447.6				3783.01			

4.5. Results: analysis and discussion

The effect of each factor selected on the tensile properties of weft-knitted reinforced composites is shown in the diagrams presented in Figure 15. The levels of each factor in the diagrams are represented by the grey and black dots according to Table 7.

Table 7. Relationship between factors and levels

Factors	Levels	Colour
Knitted structure	1x1 jersey	Grey
	Jersey	Black
Testing direction	Wales	Grey
	Courses	Black
Pre-tension	0%	Grey
	20%	Black
Number of layers	1	Grey
	2	Black

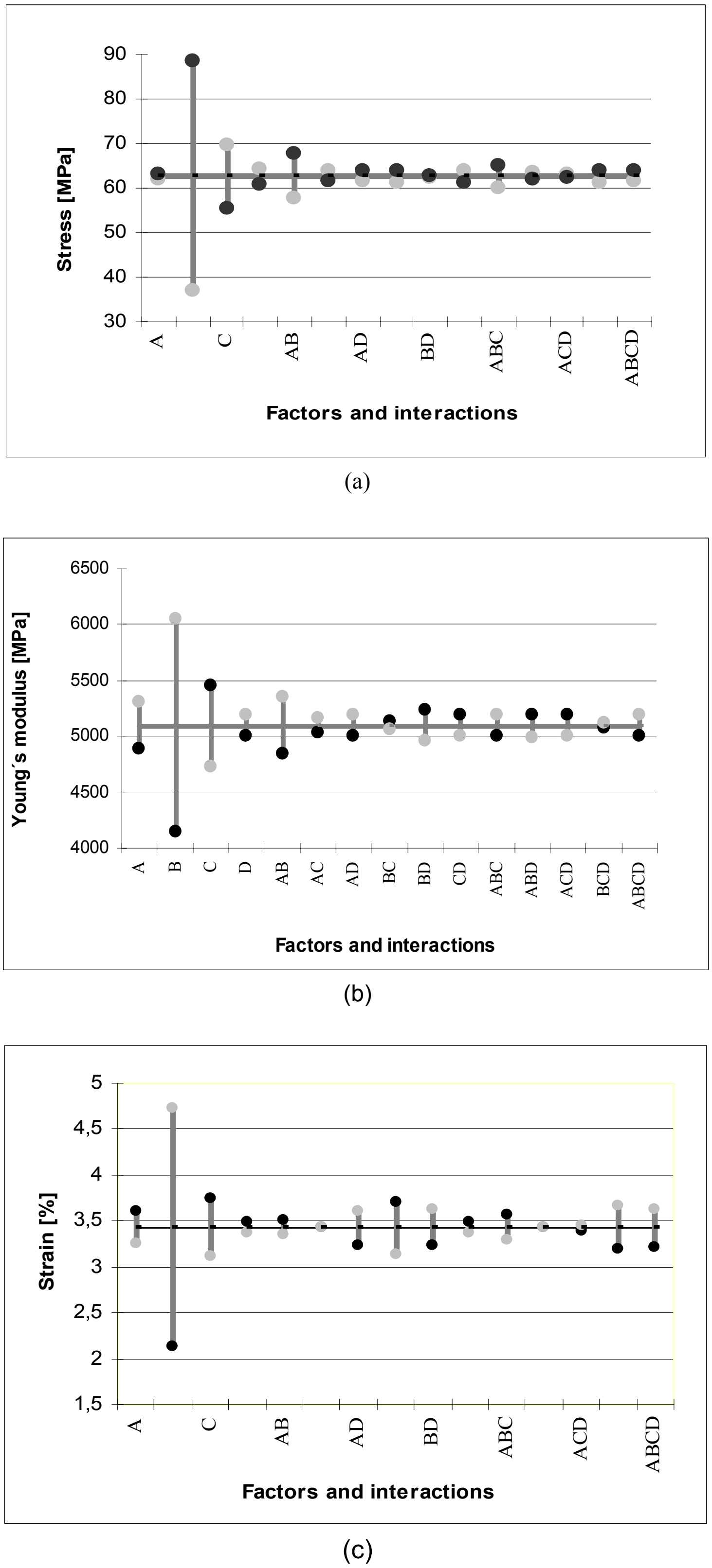


Figure 15. Effect of each factor on the tensile properties
(a) Effect on tensile strength; (b) Effect on Young´s modulus; (c) Effect on extension
A - knitted structure B – testing direction C – pre-tension D – number of layers

Analysing the diagrams, it is possible to conclude that:

- The tensile strength is strongly influenced by the testing direction and the level of pre-tension in the reinforcement (see Figure 16). In this case, the best material is obtained when the factors are as follows: jersey, walewise, 20%, 2 layers.
- Young´s modulus is influenced by the testing direction, the reinforcement pre-tension and, at a lower rate, by the type of knitted structure. In this case, the best material is obtained when the factors are as follows: jersey, walewise, 20%, 1 layer.
- The extension at break is influenced by the testing direction, the reinforcement pre-tension and, at a lower rate, by the type of knitted structure. In this case, the best material is obtained when the factors are as follows: jersey, coursewise, 0%, 1 layer.

Furthermore, in the case of the fleece structures, it is possible to use a conventional yarn in the ground structure and a high performance fibre yarn for fleece as reinforcement without significantly decreasing the tensile performance in that direction. In order to demonstrate this, a composite material reinforced by a fleece structure with conventional polyester in the ground and glass fibre yarn in the fleece has been prepared and tested. The results are shown in Table 8. Figure 17 shows the load-extension curves for the composite materials reinforced by glass/glass fleece and by glass/polyester fleece.

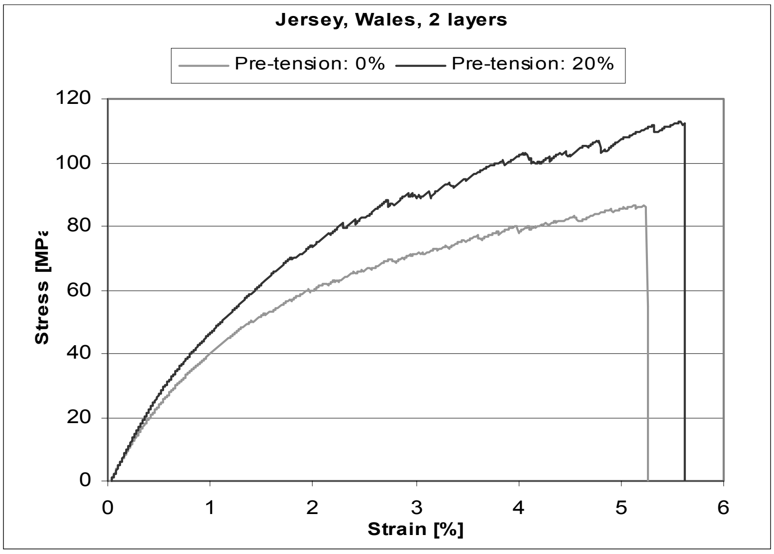


Figure 16. Influence of pre-tension on tensile behaviours of a jersey reinforced composite material

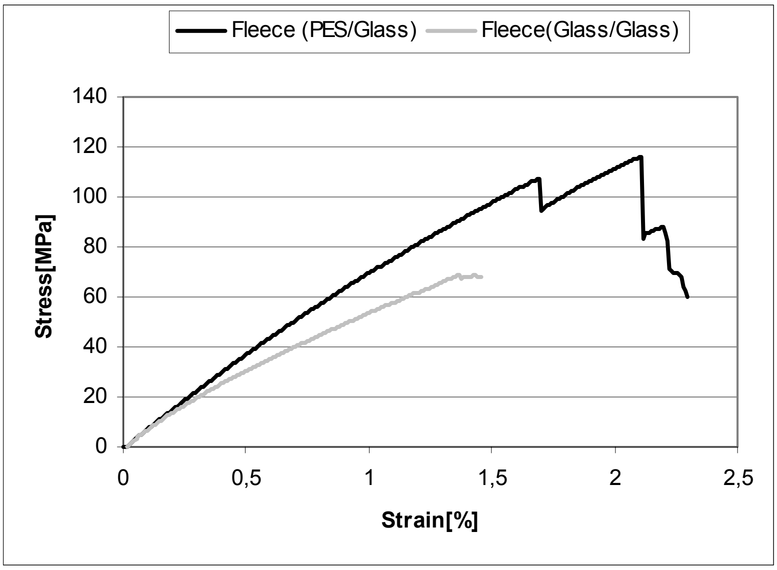


Figure 17. Stress-strain curves for the composite materials reinforced by glass/glass fleece and by glass/polyester fleece

Table 8. Tensile properties for the composite material reinforced by glass/polyester fleece

	Tensile stress [MPa]	Strain [%]	Young´s modulus [MPa]
Mean	108.18	2.26	6777
Maximum	116.17	2.65	7245
Minimum	100.71	1.83	5872
Stand. deviation	7.74	0.41	490.61
C. V. [%]	7.16	18.16	7.24

4. CONCLUSIONS

The tensile properties of glass fibre weft-knitted fabrics have been presented and discussed. According to the results obtained, their tensile properties can be improved by introducing non-knitting yarns into the ground structure. A comparison of the tensile results obtained between jersey and fleece structures confirms this approach.

The influence of several factors (type of structure, testing direction, reinforcement pre-tension level and number of layers) on the mechanical properties of weft-knitted reinforced composites has also been presented and discussed. According to the results, the factors with greater influence are the testing direction (wales or courses) and the reinforcement pre-tension level. Furthermore, composites reinforced with weft-knitted structures having non-knitting yarns present the best tensile performance. The introduction of straight non-knitting yarns and reinforcement pre-tension seem to be effective approaches to improving the tensile performance of these materials. Whether these will be sufficient will depend on the particular application (rigid matrix/flexible matrix…).

Weft-knitted preforms for composite materials may be produced using conventional fibre yarns in the ground structure, thus enabling the production of the desired shape and high-performance fibre yarns as reinforcement providing strength without losing mechanical performance.

REFERENCES

[1] Jurgen Bischoff (2003), ‘Tomorrow’s air giants’, Lufthansa Magazine, Germany, 6/2003, pag. 42-47.

[2] Fangueiro, R. (2002), ‘Optimisation of the development of weft-knitted preforms for composite materials’, PhD Thesis, The University of Minho, Portugal.

[3] Araújo, M. de, Hong, H., Fangueiro, R., Ciobanu, O., Ciobanu, L. and Moscathou, (2002), ‘The design of complex shaped fibre based preforms for composite materials’, 2nd AUTEX Conference, Belgium, 1-3 July.

[4] Araújo, M. de, Hong, H. and Fangueiro, R. (2002), ‘Improving the mechanical properties of composite materials reinforced by weft-knitted fabrics’, IFAI Forum, Charlotte, USA, October.