Experimental Research Related to the Mechanical Properties of Composite Materials Reinforced with Woven Polypropylene

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In this article we obtained the characteristic curves for polyester and epoxy resins used in the process of making composites, and determined their elastic and resistance properties as well as the characteristic curves on two directions for the epoxy and polyester resin composites, reinforced with woven polypropylene. We established the flow strain and two coefficients from the calculus relation for the plastic potential. We determined the equation of nonlinear dependency between strain and deformation in the plastic field using a fourth degree polynomial relation which indicates the specific elongation and resistance to fracture.

Keywords: composite materials, polypropylene fabric, plastic field.

Many mechanical models have been proposed as model of nonlinear behavior of composites, using two approaches, one macroscopic and the other microscopic. In the macroscopic approach, composites are treated as a nonlinear elastic or plastic body. In the microscopic approach, attempts are made to describe the effective composite response using the properties of the fiber and matrix.

In [1] it is developed the one-parameter plasticity model to describe the nonlinear behaviour of unidirectional in composite based on a more general approach [3], based on a quadratic plastic potential and the assumption that there is no plastic deformation in the fiber direction. In [3, 4] is applied the one-parameter plasticity model developed in [1] to the deformation of a composite with complex microstructure and found that the nonlinear response of the composite under creep and cyclic loading follows the associated flow rule with the one-parameter plastic potential function.

In [5, 19] it is developed a method to describe the elastic-plastic behavior of unidirectional composites and multidirectional laminates [6] consisting of aligned, continuous elastic fiber and elastic-plastic matrix. The composite is modeled as a continuum reinforced by cylindrical fibers of vanishingly small diameter which occupy a finite volume fraction of the aggregate. In [7, 8] is developed a simple micromechanical model of elastic-plastic behavior of fibrous composites. In the model, the fiber is assumed to be linearly elastic and the matrix elastic-plastic.

Compared to the models for unidirectional composites, there are few models of the plastic behaviour of woven composites. Paper [9] suggested a plasticity model for bidirectional composite laminate that requires knowledge of the axial and shear yield strength, which can be difficult to define and to obtain experimentally for composite materials. In [10] is discussed the validity of an orthotropic plasticity model of such behavior, with three parameters. The parameters have been determined from the experimental results. An attempt is also made to describe the nonlinear behavior of a woven composite as a cross-ply laminate using assumed unidirectional composite proprieties. The nonlinear behavior of the unidirectional laminate is assumed to be described by the one-parameter plasticity model. It is shown that there is a possibility that the one-parameter plasticity model can be used to predict the nonlinear behavior of woven composites.

Paper [11, 17, 18] presents a calculus relation for determining the resistance to fracture for composite plates with random distribution of reinforcement. As damage occurs, the material loses stiffness and exhibits a nonlinear, inelastic response with permanent strains after unloading. The inelastic response is the result of sliding friction at damage sites as well as any inelastic response of the constituents. Since the process is irreversible, nonlinear analysis techniques must be employed.

In [12, 15, 16] it is given a method for determining the resistance to fracture and the elasticity modulus for polyester resin plates reinforced with randomly disposed fibreglass. For some fibre-reinforced composites, in [13] it is shown the existence of a nonlinear relation among strain-deformation. In [14] it is shown that, for the epoxy boron-resin or epoxy bleak lead-resin composites, the nonlinear behaviour is because of the substance of the matrix that mainly affects the slip modulus, while the relations strain-deformation on the fibres direction, and also on the transverse direction, remain almost linear.

Experimental part

In order to estimate the resistance to fracture of a composite material, we consider that fibres have an elastic behaviour until fracture, and the matrix has a nonlinear behaviour in case of exceeding maximum deformation for the fibres fracture. In the case of a unidirectional composite stretched along the fibres, it is considered that fracture happens when the fibres fail. The practical results indicate that the maximum value of medium strain has lower values than those theoretically obtained in the previous hypothesis. The explanation consists in the fact that not all fibres have the same resistance to fracture, some give in and the intact fibres take over the entire stress.

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Table 1

Material (Resin)	Thickness (mm)	Width (mm)	Distance between supports (mm)	σ_{max} (MPa)	σ_{rup} (MPa)	ε_{rup} %	Energy (J)	E (MPa)
Epoxy	3.97	16.80	68.02	45	45	2.1	2	2604
Polyester	4.88	16.35	75.95	12	12	2	1	1036

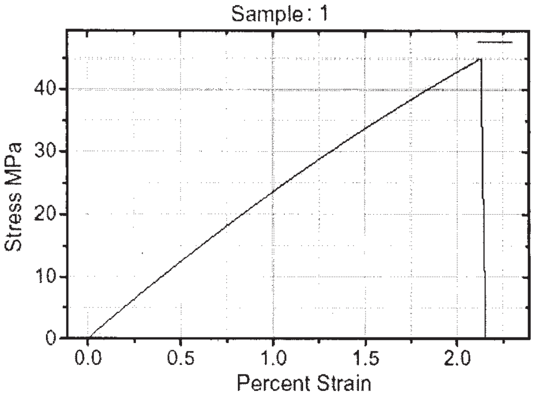

Fig. 1.

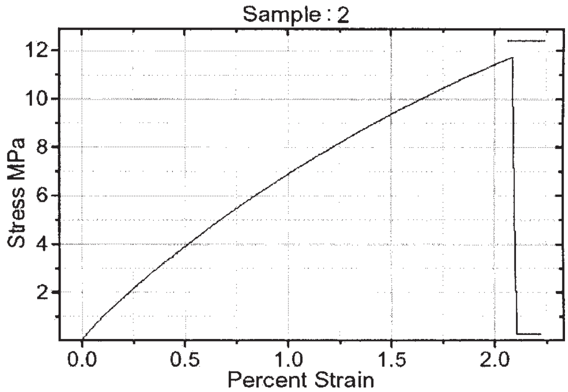

Fig. 2.

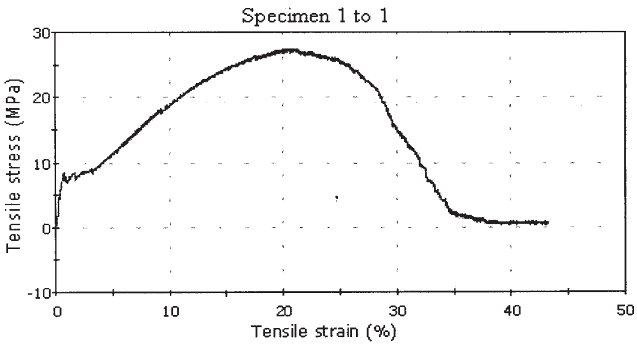

Fig. 3.

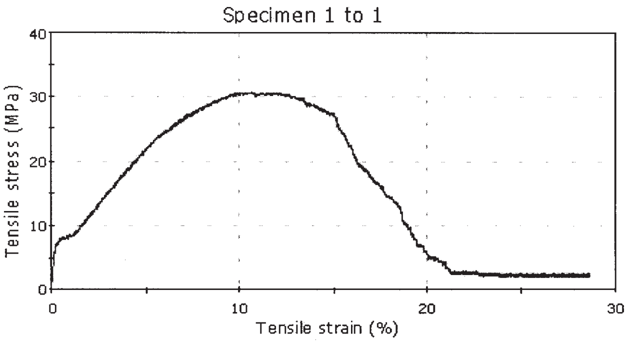

Fig. 4.

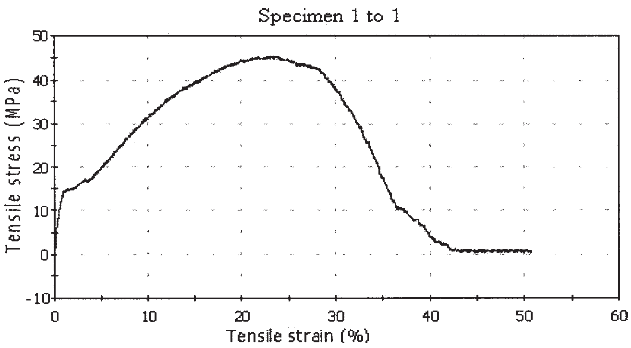

Fig. 5.

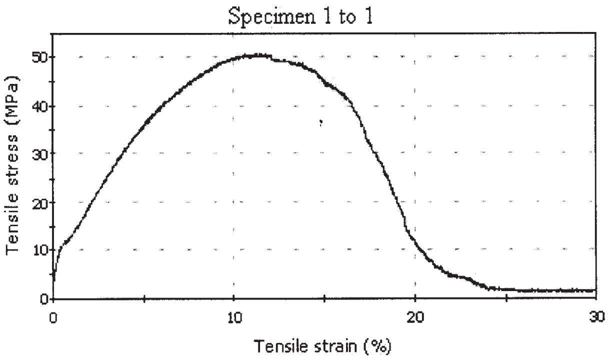

Fig. 6.

If the fibres used for reinforcement present an area of plastic behaviour after an area of elastic behaviour, then the composite material may have a nonlinear behaviour, and the theoretical determination of the resistance to fracture is very difficult. In this case, experimental determinations are necessary.

The properties of the composite materials also depend to a great extent on the matrix properties. That is why we used two sets of test boards made of epoxy resin and polyester resin, which were tested to stretching stress. The mechanic dimensions and characteristics obtained are presented in table 1. The thickness, width and distance between the supports were measured with a digital sliding calliper. The other values were read on computer after the test was completed.

In figure 1 we present the characteristic curve for epoxy resin and in figure 2 the characteristic curve for polyester resin.For both types of resin we observe a linear dependency during the entire stress until reaching the resistance to fracture. Since the resistance to fracture coincides with the maximum tension, it results that the fracture occurs suddenly, without a flow area.

It is known that in the case of polypropylene the deformation in the plastic field is quite significant. That is why composite materials armed with polypropylene fibres may present resistance properties even in the case of significant deformations.

We used composite materials with matrix made of the resins presented, reinforced with polypropylene fabric. In order to compare the experimental results, we considered that the fabric fibres on the two directions have the same volumetric proportion, but different properties regarding the specific deformation at fracture and the elasticity modulus.

The materials were made in the form of plates from which test boards were taken depending on the orientation

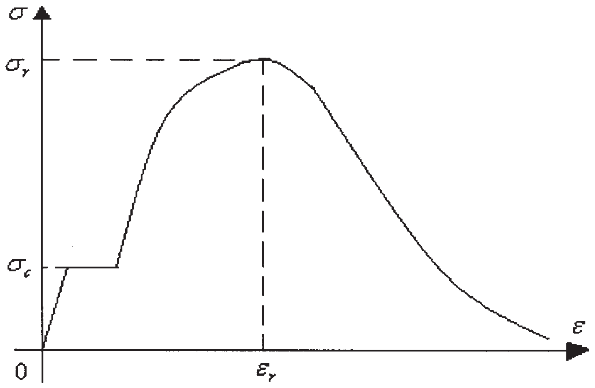

Fig. 7.

Table 2

Resin	Direction	Flow Strain (σ_c) (MPa)	Load at Tensile Strength (N)	Tensile strain at Tensile Strength (mm/mm)	Tensile stress at Tensile Strength (MPa)	Modulus of Elasticity (MPa)
Epoxy	*x*	8	1427	0.2066	27.13	1204
	y	7.5	1499	0.1112	30.36	3597
Polyester	*x*	14	2223	0.2279	45.02	1880
	y	12	2527	0.1134	50.12	3536

direction of the fabric fibres. The test boards were tested to traction on the hydraulic machine 10 T INSTRON, the speed being 2 mm / min. We used x and y to mark the two directions on which the fabric fibres are oriented.

In figure 3 it is presented the characteristic curve for the epoxy resin test boards on direction x.

In figure 4 it is presented the characteristics curve for the epoxy resin test boards on direction *y*.

In figure 5 it is presented the characteristic curve for the polyester resin test boards on direction *x*.

In figure 6 it is presented the characteristic curve for the polyester resin test boards on direction *y*.

Analysing the figures 3- 6, we observe that a theoretical characteristic curve can be proposed, of the type presented in figure 7.

We observe that, after a linear elastic behaviour, there is a flow zone at flow strain σ_c, followed by a plastic deformation zone with nonlinear behaviour. The maximum strain is considered fracture strain (σ_r), and the deformation at maximum strain is considered fracture deformation. Table 2 presents these characteristics for the considered materials.

The appearance of a flow zone can be explained by the fact that initially the fabric is not stretched, and the effort is taken over to a great extent by the matrix.

Behaviour study in the plastic field

In [10], for the study of composites' behaviour in the plastic field, we use the plastic potential in the form:

$$f(\sigma_{ij}) = a_{xx}\sigma_{xx}^2 + a_{yy}\sigma_{yy}^2 + 2a_{xy}\sigma_{xx}\sigma_{yy} + 2b_{xy}\sigma_{xy}^2, \qquad (1)$$

where the coefficients a_{xx}, a_{yy}, a_{xy}, b_{xy}, are experimentally determined.

Introducing the effective strain through the relation:

$$\bar{\sigma} = \sqrt{3f}\,, \qquad (2)$$

in [10] it is shown that for a unidirectional composite the behaviour in the plastic field can be described by means of the plasticity model proposed in [1].

Without decreasing the generality, as [10] also indicates, a_{xx} =1 can be accepted. In these conditions, for the epoxy resin material it results a_{yy}=0.9375, and for the polyester resin material it results a_{yy}=0.8571.

According to [10], a_{xy}=0.15 is accepted, and b_{xy} has values around 15. It is impossible to uniquely determine a_{xy} because this is dependent on the strain, the previously presented values being accepted.

It is shown in [10] that between the specific, effective plastic deformation and the effective strain there is a nonlinear dependency of the form:

$$\bar{\varepsilon} = A\bar{\sigma}^n, \qquad (3)$$

the coefficients *A* and *n* being determined for glass / epoxy woven composite.

Similarly, for the materials on which we made the experimental determinations, we propose a nonlinear dependency in the plastic field.

In the plastic area we consider that the dependency between strain and deformation is given by a fourth degree function which has the form:

$$\sigma = a(\varepsilon - \varepsilon_r)^4 + b(\varepsilon - \varepsilon_r)^3 + c(\varepsilon - \varepsilon_r)^2 + \sigma_r. \qquad (4)$$

We consider this form so that the extreme in function (4) should coincide with the point in which the maximum strain value is reached. It is also necessary for the function to approximate the characteristic curve as exactly as possible. For this we used the least square fit calculation method. We consider that the sum of the square differences between the proposed function and the values of the experimentally determined strains within a number of 30 dots is minimum. Table 3 presents the values obtained for the coefficients *a, b, c,* in the case of the four sets of tests.

Table 3

Resin	Direction	$a\,(MPa^{-4})$	$b\,(MPa^{-3})$	$c\,(MPa^{-2})$
Epoxy	*x*	-0.0018403	-0.0521373	-0.4422744
	y	-0.009708	-0.1756728	-1.0444197
Polyester	*x*	-0.0011472	-0.0398487	-0.4327353
	y	-0.0214643	-0.359216	-1.89999135

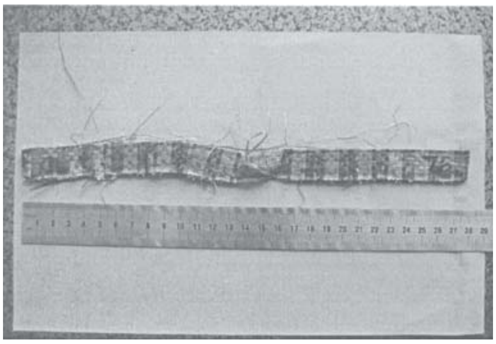

Fig. 8

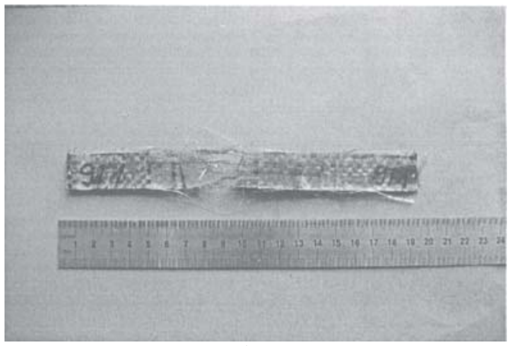

Fig. 9

We considered only dots in the area of plastic deformation with $\varepsilon < \varepsilon_m$ because, after the maximum tension is reached, the test board is practically destroyed.

Conclusions

The composite materials studied were made of matrix (epoxy and polyester) with fragile behaviour reinforced with polypropylene fibres which have a tensile behaviour.

The resins used for the matrix had a linear strain-deformation dependency during the entire test to traction, the test board breaking suddenly when reaching the fracture strain.

The reinforcement material presents a flow area in which the deformation increases very much, but the strain does not acquire significant variations.

The behaviour of the composite material obtained greatly combines the properties of the constituent materials. On direction x, the elasticity modulus is smaller than the elasticity modulus on direction y. The same phenomenon is observed for the resistance to fracture. Conversely, the elongation to fracture is bigger on direction x than on direction y. This can be explained by the fact that on direction x the properties of the polyester woven fibres are inferior (smaller, weaker) than those oriented on direction y.

The characteristic curve analysis shows that, in the area in which flow occurs, the specific fracture deformation of the matrix material is exceeded. The conclusion could be that at this stage there is a section of the test board in which the matrix material gives in, in this respective section the stress being increasingly taken over by the fibres.

The specific elongation of the tested materials, which is very high in the plastic field, is explained by the fact that, since there are several strata of fabric, these give in progressively and in different sections of the test board, as it can be observed in figures 8 and 9.

Since on direction x, as well as on direction y, the deformations to fracture of the two materials are very close, it means that, in fact, the fracture takes place when the fibres give in. Conversely, the resistance to fracture for each of the two materials on direction x is lower than on direction y. The fracture resistance values indicate proportionality with the resistance to fracture of the resins used, which requires the conclusion that the matrix influences the composite behaviour in the plastic domain as well.

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