Influence of the Geometric Parameters on the Elastic Properties of Textile Polymeric Composites

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The textile polymeric composites define a class of advanced materials, utilising fabrics as reinforcement. The geometry, as well as the structure of textile reinforced polymeric composites, are much more complex than that of composites reinforced with unidirectional fibres. The mechanical properties of textile reinforced composites are influenced by several parameters such as fibre material, the internal geometry of the fabric, number of counts, size of gap between adjacent yarns, height of woven layer, undulation and thickness of the composite lamina. Each of these factors can influence the structural behaviour and can be modelled based on its specific length scale. This paper is focused on the modelling procedures of the in-plane stiffness characteristics, specific to satin reinforced laminated composites. The method used is a compromise between the continuous and pure discrete approaches and it is associated with a mesoscopic analysis of the repetitive unit cell (RUC). The elastic properties of the textile reinforced polyester composite, using S glass fibre, arranged in satin reinforcement, are determined and analysed taking into account the variation of two characteristic geometric parameters, namely the width and the height of the reinforcing tow.

Keywords: satin textile composites, elastic moduli, geometric parameters, reinforcing tow

Composites are heterogeneous materials, created by assembling two or more components, constituting reinforcing and a compatible matrix, to obtain specific properties, which cannot be provided by any constituent working individually [1]. The forming of textile preforms requires knowledge about the structure of fibres and yarns. The mechanical properties of textile structural composites can be adequately studied by taking into account their hierarchical organization, [2-4]. Textiles are flexible, anisotropic, nonhomogeneous, porous materials, with distinct viscoelastic properties. This unique characteristic makes the textile structures behave differently than other materials, [5, 6].The complex structure of textile composites requires several hierarchical levels for studies: macro (composite component or sub-component), meso (unit cell of the reinforcement structure) and micro (fibre placement inside yarns and fibrous plies). The micro-meso-macro simulation approach, (fig. 1) has proven to be successful for predicting elastic/ mechanicalproperties, taking into account the above mentioned issues [7].

The most specific to textile composites is the meso level, where the structure dependent behaviour of the material is most pronounced. We mention here that a rigorous theory at the micro level, developed for polymer materials (hereditary theory of elasticity) [8. 9] together with simulation techniques [10], will be extrapolated in future articles, on complex structure of textile composites.

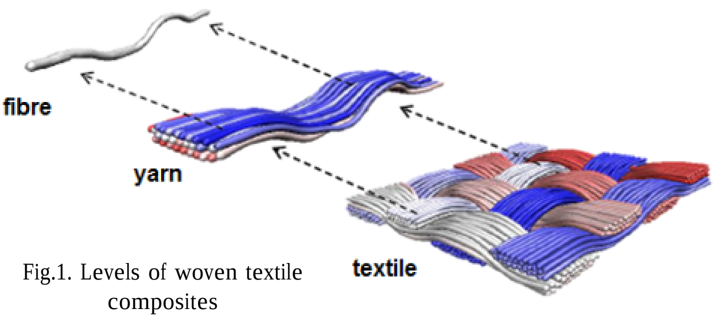

Fig.1. Levels of woven textile composites

Experimental part

Unit cell geometry

The repetitive unit cell (RUC) is the smallest possible building block of a textile composite that contains all the features necessary to completely define the composite material. The RUC is utilised to perform geometric and mechanical analysis. An entire textile reinforced composite structure can be rebuilt by replicating the RUC along the fill and warp path ways. For the composite reinforced with a variant of 5-hharness satin fabric (5/2/1), the smallest part of the fabric is represented in figure 2.

The 5 harness satin considered (5/2/1) is a planar, orthogonal, square fabric made from two perpendicular tows, each consisting of a bunch of fibres. The tows laid down in the *x* direction of the lamina are called *fill* and the tows aligned at a right angle, in the *y* direction, are called

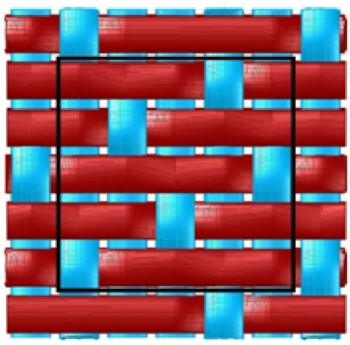

Fig. 2. The repetitive unit cell (RUC) for satin 5/2/1 reinforced composite

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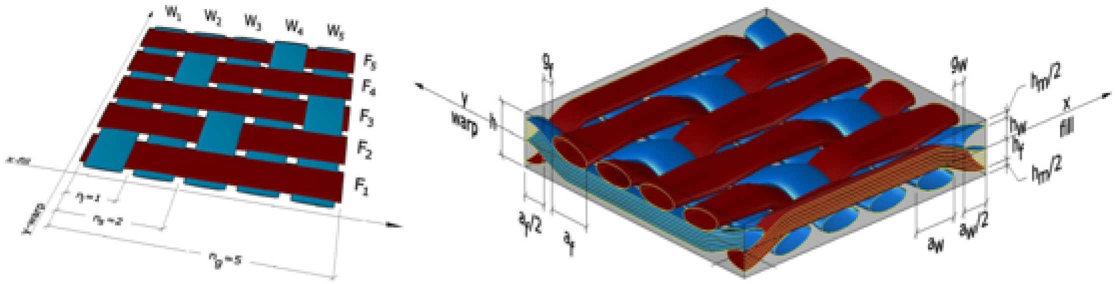

Fig. 3. The geometrical parameters corresponding to RUC

warp. The following geometric parameters (fig. 3) are introduced to facilitate the modelling and the implementation of the specific geometry in specialised software:

- n_g is the number of subcells along one direction of the RUC (harness). In the case of 5/2/1 satin, $n_g=5$;
- n_s is the number of subcells between consecutive interlacing regions (shift). In case of the 5/2/1 satin, $n_s=2$;
- n_i is the number of subcells in the interlacing region (interlacing). For satin 5/2/1, $n_i=1$;
- a_f and a_w are the tow width for fill and warp, respectively;
- h_f and h_w are the tow height for fill and warp, respectively;
- g_f and g_w are the gap between two consecutive tows for fill or warp, respectively;
- h_m is the neat-matrix thickness.

The above mentioned parameters are used for the coding system of the 2D fabrics (biaxial orthogonal).

Unit cell modelling

The textile reinforced composites can be analysed using various methods, grouped into two main categories: numerical methods (NM), based on finite element analysis, and analytical methods (AM). While NM models provide higher accuracy using less approximation, they also require discretization (mesh) for each specific case, making parametric studies cumbersome. On the other hand, AM are able to provide good agreement with experimental data, if they incorporate enough features to model the material behaviour [11].

The method adopted is a hybrid one; it was proposed by Barbero [2] and represents a good compromise between the accuracy of the finite element methods and the simplicity of the analytical methods. Due to the complexity of the geometry, the calculus quickly becomes complicated and requires the use of specific software, running on a powerful computer. Therefore, all functions that describe the fabric geometry and equations to determine various parameters of the composite were implemented in MATLAB® programming environment. The software was developed in house and the core part was to accurately define the geometry of the yarns, with their specific undulations and straights. The tows are considered having elliptical cross-sections and, by using complex functions, the lower and the upper surfaces of any fill and warp could be found, accurately describing them, as well as the presence of the gap between tows. Once the geometry is known, the composite lamina is treated as a laminate, consisting of layers of different materials (matrix, fill and warp). These materials have their specific characteristics and, by sticking them together, one can see that a single lamina reinforced with woven textile becomes a composite structure by itself. Starting from this structure, using classical lamination theory and a homogenisation method, the elastic characteristics of the composite can be determined [12].

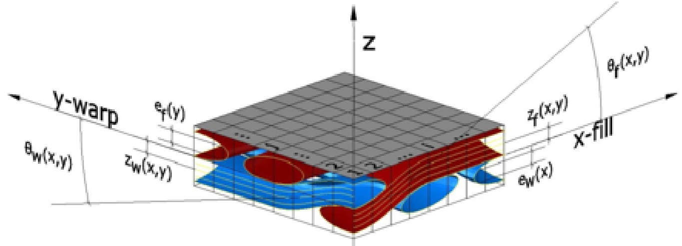

Fig.4. The discretisation of the RUC

Firstly, the RUC is divided into smaller 2D pieces, along the *(x,y)* plane, in order to better consider the undulation of the tows. The accuracy of the end results is improved by increasing the number of elements. A 50 by 50 discretisation has been performed, obtaining 2500 pieces for the entire RUC, (fig. 4).

At a specified location *(x,y)* the geometry of each of the constituents (fill and warp) are described by complex functions, starting with the undulation of the midpoint of the fill (z_f) and warp (z_w) as well as the thickness of the cross-section of the fill (e_f) and warp (e_w). Next, the tows undulation angles (θ_f, θ_w) can be calculated, as well as top and bottom surfaces bounding the fill (z_f^{top}, z_f^{bot}) and warp (z_w^{top} and z_w^{bot}). In order to find the fibre volume fraction in the fill and warp, one must firstly compute the cross sectional area and the length of the tows in the RUC, using the description given by the geometry. Once the fibre volume fraction of the tow is known, the periodic microstructure micromechanics (PMM) formulas are used to find the properties of the tow, in its own material coordinate system, necessary for building the transversely isotropic compliance matrix of the yarns. Since the tows are undulated, the transformation matrices from the laminate coordinate system to the material coordinate system are defined and applied to the compliance matrices, finally getting the reduced stiffness matrices for the fill and warp, for every possible *(x,y)* coordinate of the smaller pieces of the RUC. In the next step, every 3D element defined by a 2D small piece times the thickness of the lamina (h) is analysed using classical lamination theory. The 3D element is treated as an asymmetric laminate with four layers and laminate stacking sequence depending of the *(x,y)* position, using a bending restrained model. The elastic moduli E_x, E_y and G_{xy} of the laminate are obtained by assembling the stiffness of all elements in the RUC by using an isostrain assumption, that is to assume that all elements are subjected to the same in-plane strain (ε_x, ε_y, γ_{xy}).

Results and discussions

A parametric study has been performed to analyse the influence of the fabric geometric parameters on the elastic constants of an woven fabric reinforced polymeric composite material, paving the road to the best solution for particular situations. The study refers to a polymeric composite made of S-glass fibres as reinforcement and a polyester matrix. The properties of the constituents as well

Composite material	E [GPa]	a_f [mm]	a_w [mm]	g_f [mm]	g_w [mm]	h_f [mm]	h_w [mm]	h_m [mm]	$V^{f,w}_{fiber}$ [-]
S glass-polyester	S-glass fibres: E_f = 85.5 Polyester matrix: E_m= 3.0	0.4	0.4	0.25	0.25	0.043	0.043	0.000	0.70

Table 1
ELASTIC AND GEOMETRIC PARAMETERS OF THE COMPOSITE CONSTITUENTS

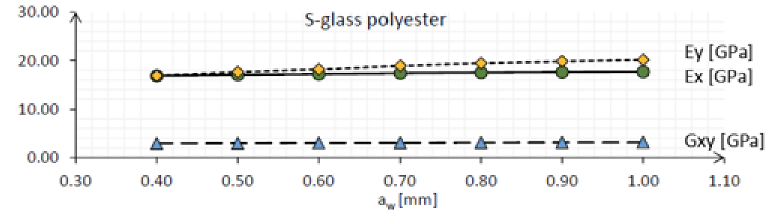

Fig. 5. Variation of the stiffness properties of composite with respect to a_w

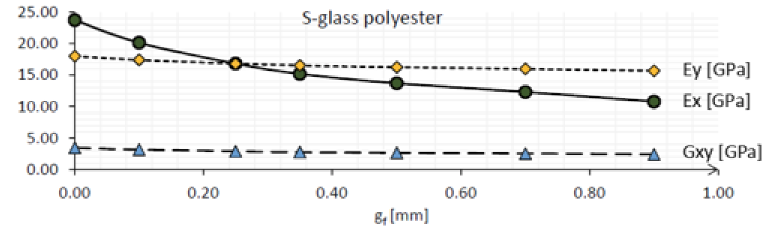

Fig. 6. Variation of the stiffness properties of composite with respect to g_f

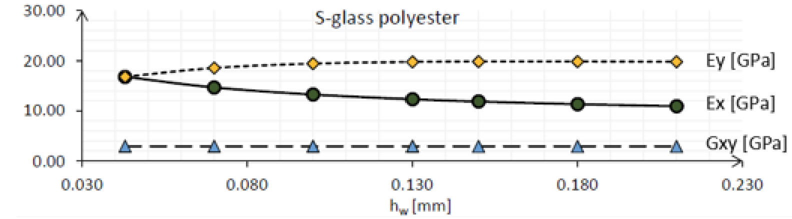

Fig. 7. Variation of the stiffness properties of composite with respect to h_w

as the geometric parameters of the RUC are given in table 1.

Multiple values for the independent parameters such as yarn width, yarn spacing, yarn height and the gap between yarns, have been selected, while freezing the other parameters. The influence on the stiffness properties of the composite, considering the above mentioned variable parameters, has been evaluated.

Variation of the stiffness properties with respect to one variable parameter

A study based on single variably geometric parameter has been firstly carried out. The obtained results are given in table 2 and illustrated in figures 5, 6 and 7.

Variation of the stiffness properties with respect to two variable parameters

The analysis of the stiffness properties has been extended to involve two variable parameters. In this case, the first parameter considered is the width of the warp tow (a_w = 0.40 to 0.80 mm) and the second one is the height of the warp tow (h_w = 0.043 to 0.210 mm).The results are illustrated in figures 8, 9 and 10.

Different families of curves have been obtained after applying the procedure described before, when the two parameters have been changed. Figure 8 illustrates the variation of the elastic modulus E_x when a_w and h_w increase within the ranges specified in this case study. These curves show that increasing a_w and maintaining h_w lead to higher values of E_x. (the maximum value of Ex is obtained for h_w = 0.043 mm and a_w = 0.80 mm, while the minimum value of this property corresponds to a_w = 0.40 mm and h_w = 0.210 mm). However when a_w is kept constant and h_w is increased, the value of this elastic magnitude decreases. Intermediate values of E_x can be determined when both parameters increase simultaneously.

Variable geometric parameter [mm]	E_x [GPa]	E_y [GPa]	G_{xy} [GPa]
a_w (Fig.5) from 0.40 to 1.00	*small relative increase* *(5.00%)* from 16.81 to 17.65	*significant relative increase* *(19.75%)* from 16.81 to 20.13	*very small relative increase* *(0.09%)* from 2.91 to 3.18
*g_f (Fig. 6) from 0.00 to 0.90	*high relative decrease* *(54.70%)* from 23.73 to 10.75	*significant relative decrease* *(13.00%)* from 17.99 to 15.75	*high relative decrease* *(30.20%)* from 3.49 to 2.42
h_w (Fig. 7) from 0.043 to 0.210	*significant relative decrease* *(20.90%)* from 16.81 to 10.93	*significant relative increase* *(15.20%)* from 16.81 to 19.83	*constant* *(0.00%)* 2.91

Table 2
VARIATION OF THE STIFFNESS PROPERTIES WITH RESPECT TO ONE VARIABLE PARAMETER

*equal values for the elastic moduli (E_x = E_y = 16.81 GPa) have been obtained for g_f = 0.25 mm

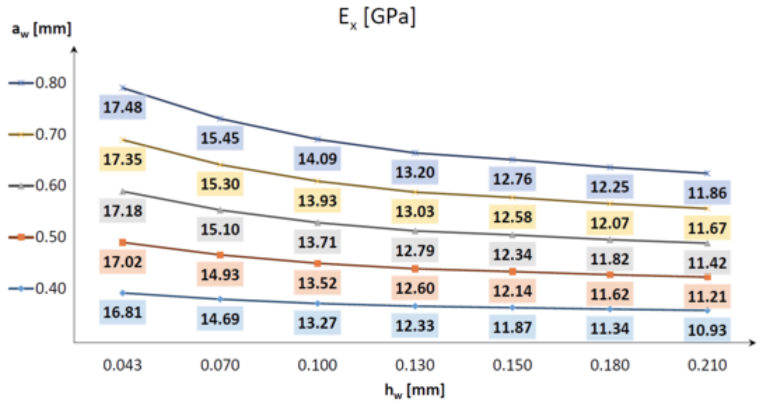

Fig. 8. Variation of E_x of composite with respect to a_w and h_w

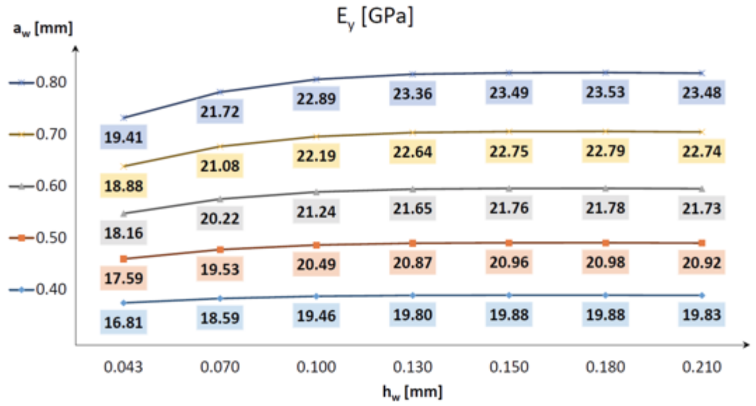

Fig. 9. Variation of E_y of composite with respect to a_w and h_w

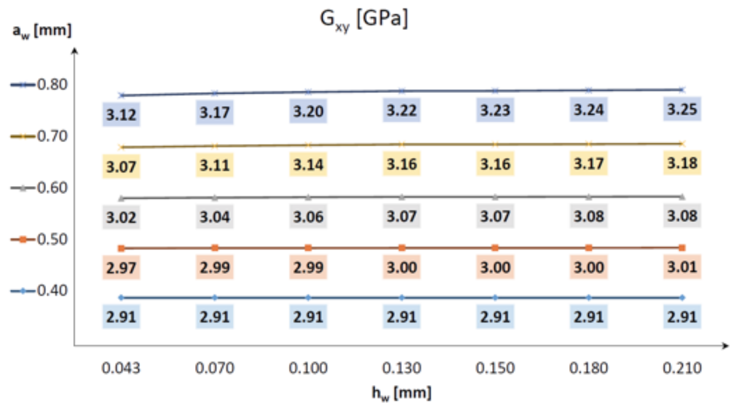

Fig. 10. Variation of G_{xy} of composite with respect to a_w and h_w

The family of E_y curves, when a_w and h_w are variable, show an increase of this property.The maximum value of E_y is obtained for h_w = 0.210 mm and a_w = 0.80 mm, while the minimum value of this property corresponds to a_w = 0.40 mm and h_w = 0.043 mm. By comparing the curves illustrated in figure 8 and figure 9, it can be noticed that the increase of a_w leads to higher values of both elastic moduli, E_x and E_y, while the increase of h_w reduces E_x and magnifiesE_y. The relative decrease of E_x is between 32% and 35% while the relative increase of E_y is between 15.2% and 17.3%.

The variation of shear modulus G_{xy} proves the beneficial influence of the textile reinforcement on the stability of shear properties. The maximum variation of G_{xy} on the studied range of a_w and h_w is equal to 4%, while a constant value for the shear modulus is obtained when a_w =0.40 mm, even if h_w is modified from 0.043 mm to 0.210 mm.

Conclusions

The textile reinforced polymeric composite are advanced materials with great structural applications. The geometry of the fabrics reinforcing the composites enables a rational balancing between stiffness properties in principal directions. By modifying some geometric parameters, a controlled variation of the elastic moduli can be achieved in most cases.

When the variable parameter is the warp tow width, a relatively small increase is obtainedfor the elastic modulus in the fill direction, E_x and a significant increase for the elastic modulus in the warp direction, E_y while the shear modulus G_{xy} varies very little.

If the height of the warp tow increases, a significant decrease is calculated for the elastic modulus in the fill direction, E_x; also an important increase for the elastic modulus in the warp direction, E_y has been noticed. As it has been shown, the shear modulus of the elasticity, $G_{xy,}$ is practically constant.

The influence of the variation of the fill gap is materialised by high relative decrease of the elastic modulus in the fill direction, significant relative decrease of the elastic modulus in the warp direction; a relative high decrease of the shear modulus has been determined.

The simultaneous increase of both parameters leads to permanent decrease of the elastic modulus E_x. A different effect occurs when the elastic modulus E_y is analysed, namely all calculated values show an increase with magnification of the warp width and the warp height. The values of the shear modulus of the elasticity, G_{xy}, show little variation, proving the effectiveness of the textile reinforcement on the uniformity and stability of the shear stiffness.

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