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Effect of Hybridization on Stiffness Properties of Woven Textile Composites

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Abstract The present study focuses on stiffness properties of woven textile reinforced polymeric composites with respect to hybridization, and geometry of reinforcement. The analyzed composites represent combinations of different fibre materials (E-glass, Kevlar 49, carbon HM) in a predetermined fabric geometry (a plane weave embedded in thermosetting polymeric resin) serving controlled properties and required performance. The effects of hybridization on the stiffness properties of woven textile composites have been studied with respect to the fibres materials, the unbalancing degree of fabrics, and the variation of compactness and undulation of yarns. Some undesirable effects in fabric geometry can be overcome by the combined effects of hybridization and compactness.

Keywords Composite materials · Hybrid reinforcement · Woven fabric · Textile composites · Elastic stiffness

1 Introduction

The maps of engineering properties of materials display the ranges of mechanical behaviour they cover; these maps reveal that there are empty areas of property space [1, 2].

Composites are heterogeneous materials created by the assembly of two or more components constituting reinforcing and a compatible matrix, to obtain specific characteristics and properties which cannot be obtained by any constituent working individually [3, 4]. Fibre reinforced composite materials represent a radical approach to designing structural materials when compared to traditional ones. The layers may be composed of long fibres embedded in a matrix under different architectures, fibre reinforced composites exhibiting quasi-isotropic or anisotropic behaviour. [3]

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The term "textile structural composite" identifies a class of advanced composites utilising fibre performs for structural applications Fig. 1, providing adequate structural integrity shape ability, better out-of-plane stiffness, strength and toughness properties [2, 3, 5]. The properties of a fabric are the properties of fibres transformed by the textile structure [6, 7]

In contrast to composites reinforced with unidirectional fibres the geometry and structure of textile composites is much more complex and mechanical properties of textile polymeric composites are influenced by several parameters and phenomena such as: fibre architecture or internal geometry of fabric, the linear density, number of counts, as well as size of gap and plastic flow of polymeric resin. Each of these can influence the structural behaviour, but can only be modelled on its specific length scale.

2 Hybrid Reinforcement

Different combinations of materials and of their associated properties to reach values unattained with individual materials can be achieved using the paths A, B, C and D shown in Fig. 2; A corresponds to the peak values of properties P_1 (of material M_1) and P_2 (of material M_2). Each path can be formulated and characterized by linear (A, C, D) and/or non linear (B) analytical models [1].

In the case of reinforcement, by combining two or more types of fibres, it is possible to club advantages of materials while simultaneously mitigating their less desirable qualities. However, there are still domains of characteristics "uncovered" by such solutions and the "hybridization" process is a welcome way of solving [2]. A hybrid textile composite material can be obtained as a combination of two or more fibre materials in a predetermined geometry and scale.

The advantage of hybrids is that the superior properties of each fiber material can be utilized to optimize the composite product. Depending on the application requirements the hybrid textile reinforcements can be optimized using two different isotropic or anisotropic materials in the orthogonal directions or combinations of different anisotropic materials [6, 8]. The parameters analyzed in the existing models of woven textile composites include fabric weight, constituent volume fraction, yarn undulation, and weave style and properties of the constituent materials [5]. However, the hybridization further complicates the analysis by introducing new variables.

The following design and analysis steps, Fig. 3, have been proposed by the authors to make the best use of hybridization in achieving the required design properties:

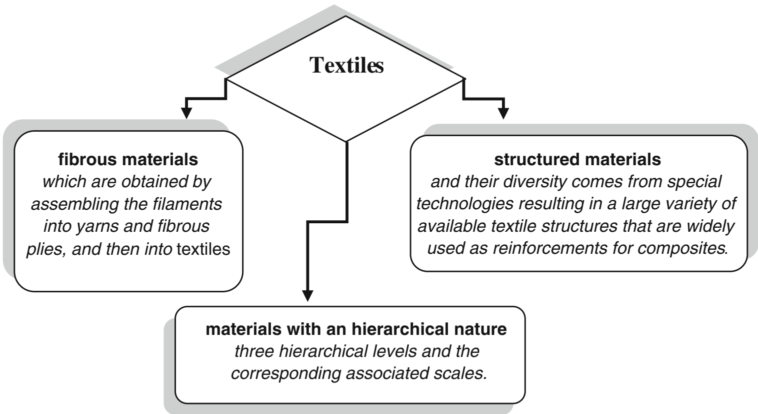


Fig. 1 Characteristics of textile reinforcement

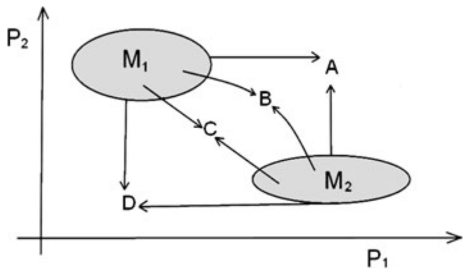


Fig. 2 The possibilities of hybridization

3 Woven Fabrics Polymeric Composites

The use of woven fabric as reinforcement in polymeric composite materials continues to expand in structural applications. Textile composites have mechanical properties different from those of unidirectionally reinforced composites. Mechanical properties of such composites are highly influenced by the details of fabric architecture. Most analytical models to determine the composite lamina stiffness are based on micromechanics analyses on representative unit cells that are different for every weave pattern, [9]. The geometry of the woven composites is complex and the choice of possible architectures is very large, Fig. 4. Different types of weaves can be identified by repeating patterns in both directions, defined by geometrical quantities (number of counts along warp, n_w, and along fill, n_f).

Various types of weaves have been developed with different handling and mechanical characteristics. These characteristics are influenced not only on the fibre's properties but also on the way in which the fibres are formed into the fabrics.

Fabric properties depend on multitude of parameters including the following: type of weaves, areal weights, fabric thickness, thread counts, variety of fibre diameters, other fibre properties for both warp and fill, and directional failure strength. This flexibility gives a large variety for numerous fabric combinations [8, 9]. Analytical models are necessary to study the effects of various parameters on the behaviour of woven composite and to select an efficient fabric structure for a specific application.

An *orthogonal two-dimensional* (2D) woven fabric consists of two sets of interlaced yarns. The lengthwise set is called *warp*, and the crosswise set, is called *fill (weft),* Fig. 5.

A plain weave fabric consists of two orthogonal systems of interlacing yarns, following a certain periodical pattern, Fig. 4. The structure of this fabric has been conceived either balanced or unbalanced depending upon the number of counts ($n_1 = n_w$, $n_2 = n_f$) along both orthogonal directions [3].

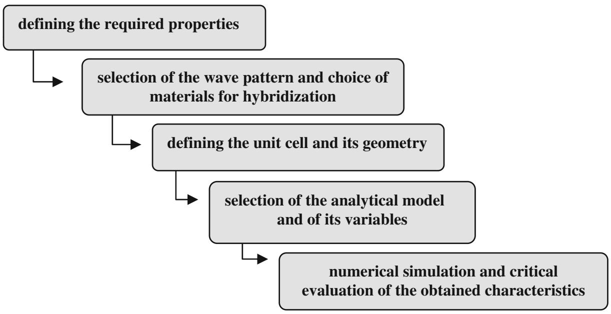


Fig. 3 The strategy of hybridisation

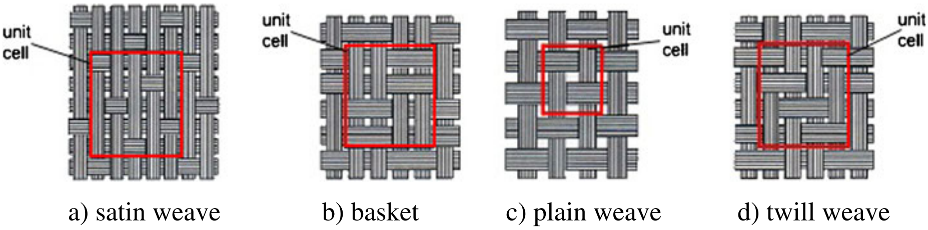


Fig. 4 Weave patterns

The authors analyze a hybrid 2D orthogonal plain weave lamina in which the warp and fill fibres materials are identical or different. Combinations of three types of fibres (E-glass, Kevlar 49, carbon HM), in a plane wave embedded in a thermosetting polymeric resin are studied.

Glass fibres are advantageous due to their lower cost and high tensile strength; carbon fibres have superior strengths, high moduli and excellent fatigue properties [10]; Kevlar fibres have high ultimate strain, ability to deform plastically, being recommended for impact loading, [1, 2, 6]. The hybridization effect has been studied keeping E-glass in the fill direction and utilising E-glass, Kevlar 49 and carbon HM in the warp direction.

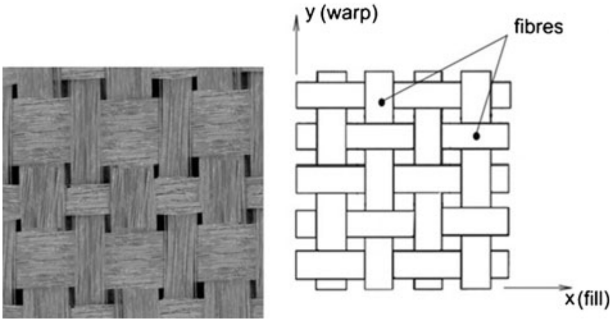
4 Lamina Configuration

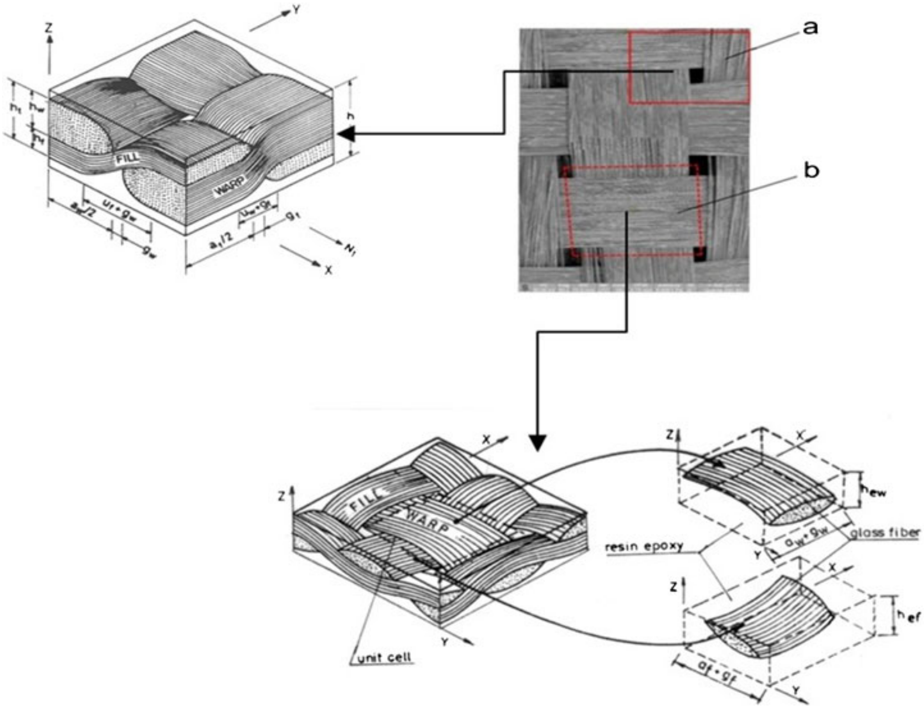
The present study focuses on stiffness properties of plain weave textile reinforced polymeric composites with respect to hybridization, and geometry of reinforcement. The chosen fabric was a plain weave with the following geometrical characteristics, Fig. 6a:

- h represents the composite lamina thickness $h=0.5\ cm$;
- h_t, represents the plane woven fabric thickness, $h_t=0.5\ cm$;
- a_w, a_f represent the dimensions of warp and fill yarn in the representative unit cell: $a_w=1.6\ cm$, $a_f=1.2\ cm$;
- g_w, g_f are the gaps between two adjacent yarns: $g_w=0.12\text{-}0.35\ cm$, $g_f=0.2\text{-}0.6\ cm$;
- u_w ,u_f represent the undulation of fibre in both directions: $u_w=0.6\text{-}1.12\ cm$, $u_f=0.6\text{-}1.44\ cm$.

Elastic properties of the studied hybrid woven textile reinforced composite have been predicted using the *stiffness averaging* method [11], earlier developed by the authors. This method transforms the unit cell into two elementary sub-laminae, Fig. 6b; for each of the two

Fig. 5 Plain weave and their two systems of yarns





a) geometric characteristics of the unit cell b) unit cell decomposed into sub-laminae

Fig. 6 The unit cell of plain weave fabric. **a**) geometric characteristics of the unit cell. **b**) unit cell decomposed into sub-laminae

plies, the local stiffness matrix and the global composite stiffness matrix has been calculated using stiffness averaging.

As stated earlier the objectives of this work have been focussed on analyzing the influence of hybridization based on different types of isotropic and anisotropic fibres on the lamina stiffness with respect to various parameters such as the number of counts in warp and fill directions, compactness (C_w, C_f) in the warp and fill directions, as well as the crimp degree expressed by undulation u_f, as defined below:

- the fabric count, representing the number of yarns per unit length along the warp, n_1, and fill direction, n_2;
- the yarn crimp which is a measure of the degree of undulation (the undulated length within the interlacing region is u_w along warp direction and u_f along fill direction);
- the compactness of fibres in yarns is C_f and C_w respectively.

The most important parameters that influence the composite stiffness [5, 9] considered in this hybridization simulation are the properties of constituents, Table 1, and the fabric characteristics.

A special simulation setup was developed in Microsoft Visual C++ 6.0 IDE. This application enables establishing different sets of variable parameters and their evolution as well. Unfeasible practical combinations of parameters or those which imply obtaining unrealistic characteristics of the simulated structures are excluded automatically.

Table 1 The main properties of hybrid textile composites constituents [3]

Material	Longitudinal elastic modulus, E_l (GPa)	Transverse elastic modulus, E_t (GPa)	Shear modulus of elasticity, G_{lt} (GPa)	Poisson's ratio ν
E-glass	72.4	72.4	27.7	0.22
Kevlar 49	130	5.4	12	0.4
Carbon HM	390	6	20	0.35
Epoxy resin	3.5	3.5	1.3	0.35

5 Results and Discussion

The selected elastic modulus of the matrix for this simulation corresponds to the most utilized thermosetting polymeric resins in structural applications (epoxy, polyester, vinyl ester). However, having in mind the negligible effect of matrix on the lamina stiffness, only an average value of matrix modulus (E_m *=3.5 GPa*) characterizing all mentioned matrices has been utilized in our graphical representations.

A *reference model based on a 3x3 E-glass balanced fabric* has been selected to reveal the hybridization effects.

The hybridisation has been gradually achieved by replacing the isotropic glass fibres placed on the warp direction with carbon and Kevlar, Figs. 7 and 8. The latest case study includes only anisotropic fibres made of Kevlar and carbon.

In addition to the hybridization phenomenon, the influence of other parameters such as number of counts (n_1), compactness (C_w) and undulation (u_f) has been analyzed. The main results obtained from numerical modelling are illustrated in Figs. 9, 10, 11.

In the first simulation the number of counts n_1 of warp has been considered variable, from *3 to 6*, while the number of fill counts n_2 has been kept constant and equal to *3*, [9]. For the balanced fabric the increased stiffness is given only by hybridization due to the use of different fibre materials, while in case of the same reinforcing material the variation of stiffness is caused by both, the fibres material and the unbalancing degree.

The variation of stiffness due to the hybridization effect (for $n_1=n_2$) changing the fibres materials gives an increase of stiffness E_y equal to *63.13 %* in case of Kevlar 49 fibres in the warp direction and *346.52 %* in case of carbon HM in the warp direction. When n_1 is variable, the fabrics become unbalanced, and more significant stiffness increases are

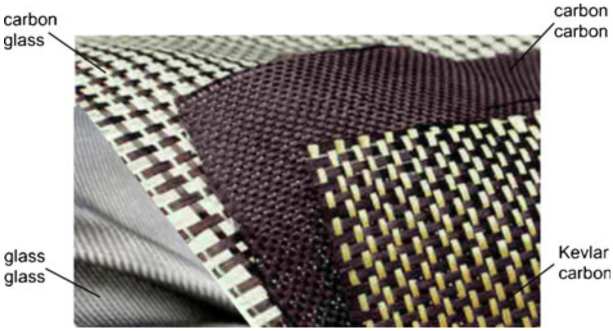


Fig. 7 Hybrid textile reinforcement

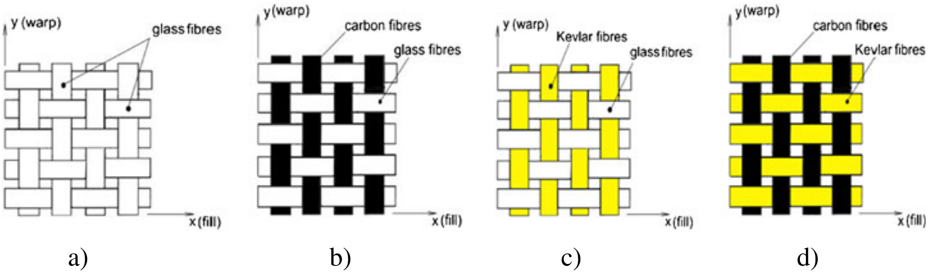


Fig. 8 Hybrid weave modules analysed in the paper

achieved: when the wrap fibres are made of E-glass the increase in stiffness is *22.61 %,* in case of Kevlar 49 the variation is *26.72 %* and for carbon HM the increase is *30.95 %.*

The most substantial gain in stiffness, (*484.76 %),* compared to all E-glass fibres balanced fabric, is obtained when the warp fibres are made of carbon HM and $n_1=6$ while maintaining $n_2=3$ and E-glass in fill fibres.

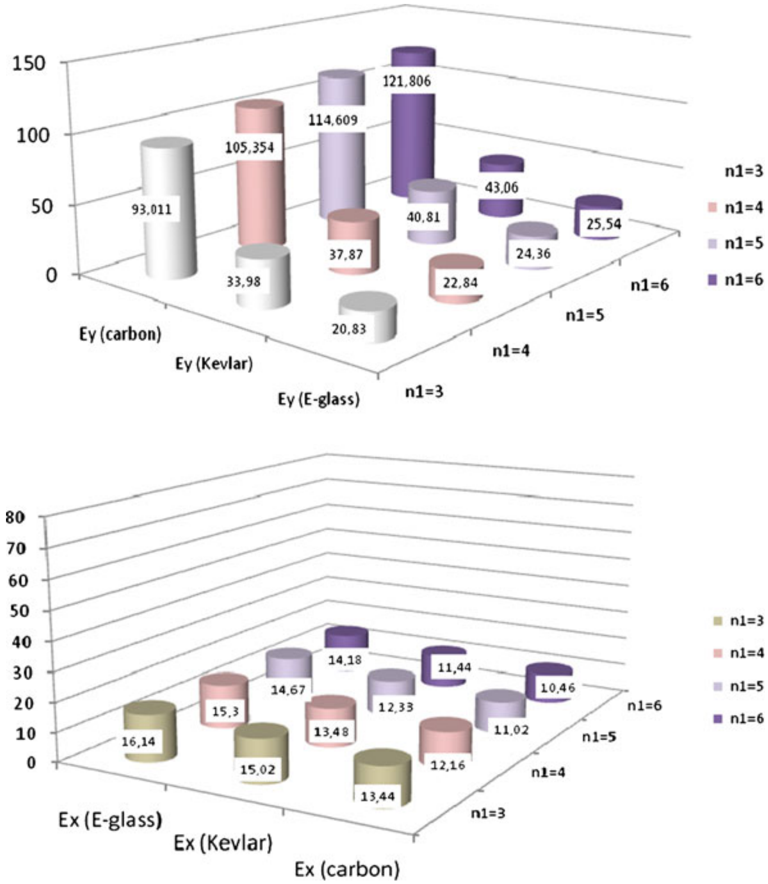


Fig. 9 Influence of hybridization and of number counts in the warp direction on the elastic moduli

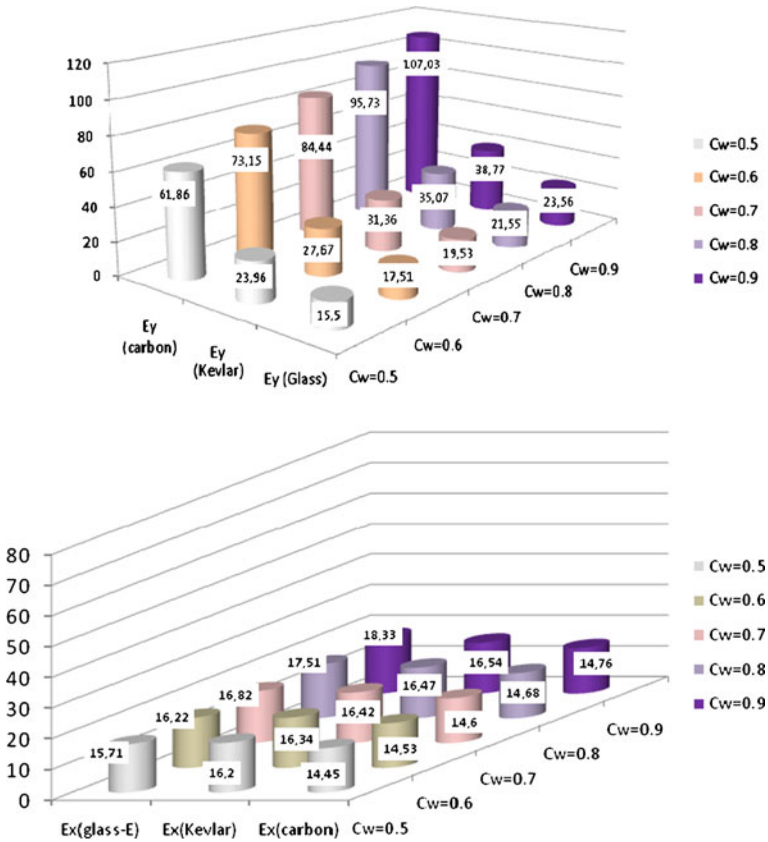


Fig. 10 Influence of hybridization and of warp compactness on the elastic moduli

Although the hybridization and the variation of counts has been carried out only in the warp direction, the effects can also be noticed in the fill direction: a light increase in stiffness E_x can be observed due to material change and also a small decrease due to increase of n_1, Fig. 9.

In the second numerical simulation the hybridization and the variation of compactness (C_w=*0.5-0.9*) have been performed only in the warp direction for a balanced fabric ($n_1=n_2=4$). The effects can be noticed in both directions, Fig. 10. A significant gain in stiffness E_y can be observed on warp direction (E-glass with E-glass gives an increase of *53.15 %;* E-glass with Kevlar 49 gains *62.58 %* in stiffness while E-glass with carbon HM leads to a modulus increase equal to *73.36 %).* The "lateral effect" of the warp yarn compactness causes a light increase of E_x.

The undulation or waviness of the yarns causes bending in the yarns, which reduces the mechanical properties of the composite. Therefore in the third simulation the authors have analyzed the influence of the fill undulation on the composite stiffness.

It has been found out that the elastic modulus in the warp direction changes as it follows: E-glass with E-glass gives a decrease of *23.55 %;* E-glass with Kevlar 49 loses *26.02 %* in stiffness while E-glass with carbon HM leads to a modulus decrease equal to *28.47 %.*

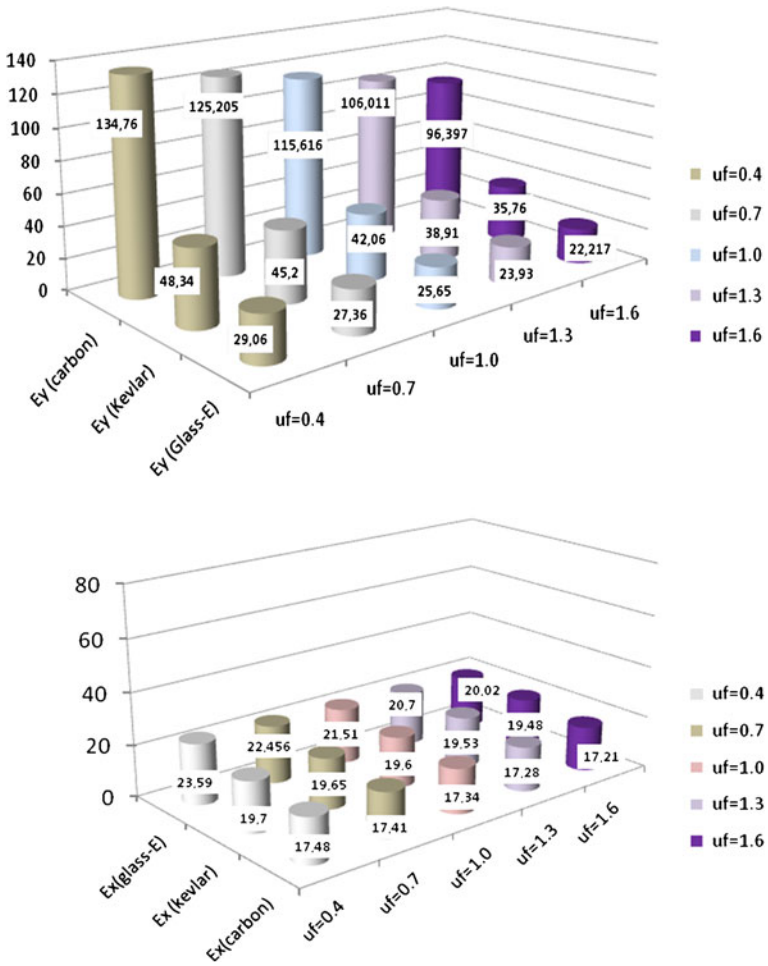


Fig. 11 Influence of hybridization and of fill undulation on the elastic moduli

At the same time a very small decrease of the elastic modulus E_x can be observed, as illustrated in Fig. 11. Such effects can be overcome by hybridization that compensates the loss of rigidity due to crimp influence.

6 Conclusions

In summary, it can been stated that the nature of material for reinforcing fibres has a significant influence on the stiffness properties of hybrid textile composites and hybridization is an important tool in obtaining tailored properties required by a specific application.

For the balanced fabric the increased stiffness is given only by hybridization due to the use of different fibre materials, while in case of the same reinforcing material the variation of stiffness is caused both, the fibres material and the unbalancing degree.

However the crimp effect due to weaving decreases the stiffness in all directions of the composite product. This undesirable influence can be overcome by the combined effects of hybridization and the variation of compactness.

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