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STIFFNESS PROPERTIES OF INTRAPLY WOVEN HYBRID COMPOSITES BY NUMERICAL HOMOGENISATION

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Abstract: Hybrid fabrics represent a rapidly emerging branch of reinforcements for composite materials. A justified use of these textiles requires good understanding of their behaviour and their modelling tools. Hybrid composites have significant strain differences amongst their phases. The lack of information on the applicability of the homogenisation methods in finite element and meso-mechanical models in predicting the mechanical properties of Intraply Woven hybrid Composites (IWHC) has provided the motivation for this study. The emphasis was put on developing FE model, while investigating other meso-mechanical models concerning their efficiency, accuracy, applicability and limitations. Results were obtained from FEA and meso-mechanical models. Tensile testing was conducted to characterise the properties and mechanisms of failure for different carbon content hybrid composites.

1. Introduction

Carbon composite materials show high specific strength and stiffness. However, since they comprise brittle fibres in a brittle matrix, they can be susceptible to impact damage. Attempts to improve the carbon performance have included modifications to fibre-matrix interface, [1] the fabrics, [2] and the fibres. The use of hybrid composites is another direction, [3]. Hybrid composites include fibres of different types in reinforcement; hence it becomes possible to combine the advantages of the different fibres while simultaneously attenuating their less desirable qualities.

Hybrid composites can be classified into two main categories: interply and intraply structures. There has been significant work dedicated to study the mechanical behaviour and properties of unidirectional and cross ply intraply hybrid composites [4]. However the case of intraply woven hybrid composites and the effect of their constituent's contents and type of fibre intermingling have not been considered satisfactorily in the literature. Therefore it is vital to further the understanding of the behaviour of intraply woven hybrid composites and their modes of damage under different loading conditions. This will assist the designer in selecting the most appropriate material for specific applications.

Hybrid composites have significant strain differences amongst their phases. The lack of information on the applicability of the homogenisation methods in finite element and meso-mechanical models in predicting the mechanical properties of Intraply Woven hybrid Composites (IWHC) has provided the motivation for this study. Emphasis in this study has been put on developing FEM, while investigating other meso-mechanical models concerning their efficiency, accuracy, applicability and limitations.

Varieties of models are available in the literature for modelling the mechanical behaviour of textile composites. The majority are still based on laminate theory and orientation averaging techniques (the latter sometimes referred to as fabric geometry models). Most of the orientation averaging schemes assume the existence of a constant stress or strain state throughout the material unit cell, which overemphasises the role of the matrix or the fibre: reinforcement on the overall behaviour. Consequently, predictions carries out using iso-stress/strain models may have significant errors associated with them. In addition, they do not allow the prediction of failure. Therefore these models can only provide a very rough estimate of internal stresses, and hence cannot be used for damage and strength analysis.

In recent models, Inclusion models were applied on models of short fibres and particle-reinforced composites, as well as models for polycrystalline materials in metals applications. The Inclusion model was extended towards modelling knitted fabrics reinforced composites by Huysmans et al, [5]. Their results showed that the model is efficient and can be used for a variety of composite materials (UD, random fibre mats, knits, weaves and braids) and solved major shortcomings found in orientation averaging models. Inclusion models also abandon the iso-stress/strain assumption and allow the prediction of stiffness and failure with good accuracy. The model computational efficiency and ability in principle to be applied on other woven fabrics architecture gave it a good interest. While the method of cells predicts the micro stress field within the unit cell of a composite material using energy principles, and originates from the work of Aboudi and Chen et al, [6]. They were the first to propose a mechanistic solution (using the complementary variational principle) as opposed to the orientation averaging schemes. Such models have been applied up to now to composites reinforced with 2D and 3D weaves and braids. The prediction of internal stress fields is a unique capability of the cell method, which sets it apart from everything else available up to now. The ability of cell models to predict stresses inside the material gives them a unique advantage. These models showed that they could accurately predict the engineering constants and failure progression in a composite material.

On the other hand, Finite Element models (FEM) with different levels of detail and idealisations have been considered in literature, [7]. FEM can provide estimates of the internal stress/strain fields with moderate to good accuracy, which allows some of them to be used for progressive damage analysis. The potential of the FE method can be fully accomplished by using a geometry development tools incorporated with the FE code. Geometrical pre-processor such as WiseTex developed by Lomov et al, [8], has been developed for textile architectures, proved to be a powerful tool making a 3D visualisation of 2D woven and braided unit cells, with an initiative and user-friendly graphical editor to define the weaving or braiding pattern.

Geometrical models representing the unit cell of IWHC hybrids and their parent textile reinforced composites have been built using the geometrical characterisation data derived from experiments using Wisetex modeller, the output of the latter has been transferred to the Inclusion and Cell modelling codes. FE models were built using Ideas-8 modelling task and by importing the geometrical data from Wisetex. In an integration on the modelling methodology of woven hybrid composites Photo-grametry technique (strain-mapping) were implemented on a small unit cell of the woven fabric composite to provide useful information regarding damage initiation, damage propagation, compare strain results obtained using FE strain distribution with the strain mapping results and to identify the special problems occurring when measuring small areas.

2. FE modelling of woven fabric composites

Woven fabrics usually present orthogonal interlaced yarns (warp and weft) and the distribution of the fibres in the yarns and of the yarns in the composites may be considered regular. This allows us to apply homogenisation theories for the periodic media both to the different yarns using the Meso-mechanical model and to the fabric using simple averaging method proposed by Theocaris and Stavroulakis, [9]. Theocaris proposed a simplified analysis to estimate the effective properties of woven fabric composites using simple averaging technique and by treating the fabric as a series of cross-ply laminates and by applying a 2D plane strain analysis on their model. Kawabata et al, [10] developed a finite deformation theory to characterise the uni-axial, bi-axial, and shear deformation behaviour of a plain weave fabric. Mean while Kalidini, [11] computed the accuracy of his (helix) FE idealised geometrical model for the yarns using planner boundary conditions with an analytical model (the weighted averaging model) based on an averaged iso-strress and iso-strain assumption, [12]. Results showed that although the local stresses and strains computed with this helix model gain more insight on the internal stress distribution of complex braids, it remains an idealisation of the real structure and is therefore not necessary superior to analytical approach for strength predictions.

Whitcomb et al., [13], looked at intrinsic model parameters like the solid model type of the yarns and the numerical integration order. They performed FE three-dimensional strain analysis to predict the elastic properties of a of a plain weave unit cell. The effective material properties and strain distribution caused large normal and shear strain concentrations, which might lead to earlier damage initiation than the one, which could occur in unidirectional or cross-ply laminates. They have also been active in the development of micro-macro approaches using sub-modelling and sub-structuring techniques to improve the computational efficiency. Similarly Tan et al, [14] proposed a three-dimensional sub modelling techniques using a three-dimensional macro and micro blocks for predicting the linear elastic property of woven fabric unit cells. Meso-mechanical and numerical studies were carried out for four types of woven fabric unit cells. Results showed good agreement between Meso-mechanical and FE model and that the number of elements in the FE model doesn't affect the effective stiffness constants significantly, but the boundary conditions does, however the values for the FE model was 50% larger than those predicted by the Meso-mechanical model and the reason for that is that the FE model runs under the Iso-strain condition, which gave upper bound while the presented Meso-mechanical models, are developed under the Iso stress conditions, which gave a lower bound.

3. Experimental and numerical details

3.1. Materials used

In order to study the effect of varying fibre content ratio in intraply woven hybrid composites, carbon (C) yarns were hybridised with aramid yarns (A) in symmetric twill 2/2 fabrics having the same end/picks count of 6.0±0.3 per cm and different carbon content (Table 1 and figure1).

Table 1: Different combination of materials used, with different carbon content

SAMPLES	C % (WARP)	C % (WEFT)	C% (TOTAL)	VF %	Inter yarn porosity	FABRIC WEIGHT (g/m^2)	0^0 and 90^0 directions	Tensile in Bias direction (45^0)	AE examination
A	0.00	0.00	0.00	44.10	35.90	152.60	Y	Y	Y
C17	17.00	66.00	18.60	44.90	37.00	188.70	Y	N	N
C33	33.00	66.00	22.80	46.10	35.70	196.10	Y	N	N
C50	50.00	50.00	22.60	46.00	35.00	195.60	Y	Y	Y
C66	66.00	66.00	32.00	48.50	33.10	211.00	Y	N	N
C83	83.00	66.00	37.00	49.70	31.70	218.40	Y	N	N
C	100.00	100.00	52.0	53.00	28.30	238.60	Y	Y	Y

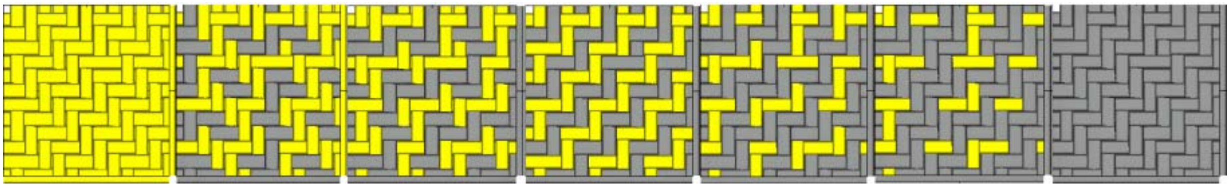

Figure 1: Codes used to name the different hybrid fabrics used

Rütapox SL-L20 matrix resin system was used to produce composite plates. The wet lay up method was used to laminate the samples. All samples consisted of 8 layers of fabric, with a total thickness of 2 mm. The fibre volume fraction varied in the range of 44 to 53%. A detailed examination was performed using optical microscopy in order to characterise the different parameters of the fabric geometry used in this investigation (Table 2).

3.2 Tensile test procedure

The effective stiffness properties and compliance matrices in the hybrid composites were determined experimentally using the method proposed by Gommers et al., [15] and Wachueux [16]. All the results (table 3) were normalised to 45% fibre volume fraction, while no scaling was done for the ultimate strain, since it was not sensitive to fibre volume fraction in the range of (10 % variation).

Tensile tests were carried out according to ISO standards [17, 18] in 2 different orientations (0^o, bias) on woven fabric samples. The results were used to derive the in-plane stiffness matrix for the composites and therefore predict the in-plane stiffness properties of IWHC. The longitudinal tensile test on all hybrids and their parent composites was carried out on the Zwick 146641 machine. Scanning electron microscopy was used to characterise the mechanism of damage in fractured samples after tensile loading.

The experimental results were used as an input to build the yarn and fabric geometries using the WiseTex geometric modeller. Geometry data (yarn packing density, fabric volume fraction in the composite, fabric weight were obtained.

Table 2: Materials specification. Geometrical and mechanical characteristics

Fabric parameters	Carbon yarns	Aramid Yarns
Weave	twill 2/2	
Ends/picks, 1/cm	6.0	
Yarns		
Yams commercial code	HTA/HTS 200	Kevlar 49
Manufacturer	Tenax	Du Pont
Linear density, tex	200	128
Yarn width, mm	1.80	1.61
Yarn thickness, mm	0.13	0.12
Fibres		
Filament diameter, µm	7	15.8
Number of the filaments in the yarn	3000	1131
Fibre density, g/cm^3	1.77	1.45
Filament tensile modulus, longitudinal, GPa	238	119
Filament tensile modulus, transverse, GPa	28	7
Filament shear modulus, longitudinal, GPa	23.5	6.3
Filament shear modulus, transverse, GPa	10.76	2.69
Filament Poisson's ratio, longitudinal/ transverse	0.3	0.3
Resin		
Tensile modulus, GPa	1.578	
Poisson ratio	0.33	
Tensile strength, MPa	40.68±2.32	
Ultimate strain, %	3.62±0.49	
Flexure strength, MPa	125	
Impregnated yarns		
Yarn's packing density, %	73.9	68.9
Impregnated yarns tensile modulus, longitudinal, GPa	176.2	82.72
Impregnated yarns tensile modulus, transverse, GPa	9.69	4.88
Impregnated yarns shear modulus, longitudinal, GPa	4.92	2.89
Impregnated yams shear modulus, transverse, GPa	3.45	1.80
Impregnated yarns Poisson's ratio, longitudinal	0.30	0.30
Impregnated yams Poisson's ratio, transverse	0.368	0.35

3.3. Building the FE geometry for the IWHC and their parent composites

FEM geometry has an important role on the results obtained from the numerical simulation. In this study I-DEAS-CAD Solid modeller was used to generate a three-dimensional solid model. The model has the potential to repeat itself in all the three directions under different loading conditions. Therefore it will be possible to incorporate different damage criterions. However due to the complicated geometrical details in modelling, the geometry was established at the yarn level. Contacts between dissimilar materials (yarns, resin or matrix) were assumed to be perfect, i.e. displacement and traction are continuous and thermal contact resistance is negligible. No defects or voids were incorporated in the model. The yarns were assumed to have regular distribution in the fabric, hence eliminating the nesting effect found in stacked laminates. In contrast to the plain weave, twill weave has its symmetry along the diagonal axis of the whole unit cell, therefore a whole unit cell were used rather than the quarter cell used in plain weaves.

In this study, the yarns were constructed from straight and sinusoidal shape function and have lenticular cross-section, the warp and fill bundles were assumed to be geometrically identical, the cross-section is kept constant, in other words, the entire cut sections orthogonal to the global x- and y-axes have the same fibre bundles cross-sections. To obtain the yarn shape function, a systematic procedure using optical microscopy has been used to obtain a 3D geometric characterisation of the woven hybrid composite. Interpolation method was used to obtain the best fitting line equation (equation 1) and (Figure 2).

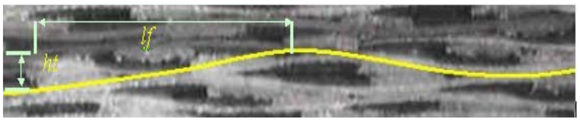

Figure 2: C50 hybrid cross-section, before interpolating the best fitting line to obtain the yarn shape function.

$$Y\,(x)=ht/2*(1-Cos\,(PI*x\,/\,Lf)) \qquad [1]$$

Where:

Lf is fibre undulation length, and ht is lamina thickness

The 3D solid models for both the warp and weft volumes (Yarns) were developed then re-oriented to construct the fabric. Subtracting yarns volume from a whole rectangular block created matrix pockets (Figure 3).

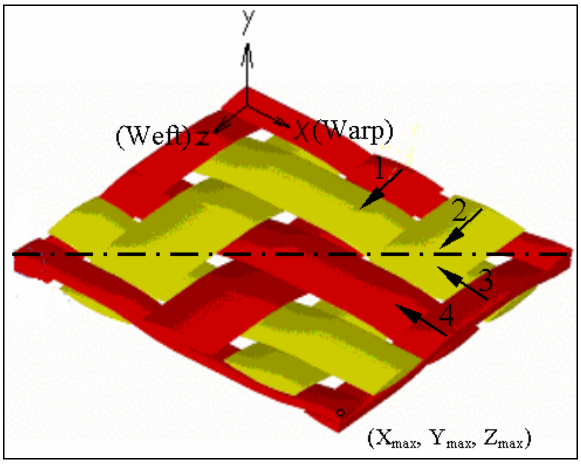

Figure 3: FEM of a repeating unit cell of a twill weave hybrid fabric reinforced composite (resin pockets are subtracted from the image), also allowing to attach to the unit cell local coordinate system.

The meshing process was generated carefully after partitioning the part into volumes representing the different materials in the unit cell. Holger Thom and Hirai et al [21, 22] examined several meshes of yarns, showing that longitudinal modulus can be influenced slightly by mesh size. In this study, the model used a total of 410,000 elements. Automatic mesh generation using three-dimensional solid parabolic element with 10 nodes, four faces, with 3 DOF was used to mesh the geometry. Refined mesh was generated using map-meshing technique at the sharp edges to avoid element's distortion. Filaments were assumed to follow a parallel path to the middle line of the yarn, and to have regular distribution in the yarns, hence it was possible to calculate yarn's effective stiffness properties using the inclusion model. The mechanical properties then were assigned to the elements.

For a general unit cell, the boundary condition has to be completely periodic. This means that displacement on one side of the unit cell should be followed by a similar displacement on the opposite side plus or minus some constant. Chapman, [19] and Carvelli et al [20] applied periodic boundary conditions on a plain weave fabric composites unit cell using constrain equations (CE) on the opposite faces. However since twill weave unit cell model has larger unit cell size compared to a plain weave unit cell, this would increase number of DOF. This resulted in technical difficulties prevented us from applying these boundary conditions due to increase in computational efficiency, mapping identical mesh on opposite faces, and applying constraint equation CE automatically on opposite faces.

Simplified conditions for the extreme condition case (free surface on a symmetrically stacked laminate) allowed us to solve the model and to get strain distribution fields. These conditions were specified as follows:

An axial displacement u_x (X_{max}, y, z) applied to the unit cell (along the warp fibres) at the X_{max} plane, allowing Poisson's ratio contractions in the y and z directions.

(X_{max}, y, z)	u=$X_{max} * \varepsilon_x$

The displacements on each of the other 5 faces were represented as:

(X_o, y, z)	u=0
(x, Y_{max}, z)	v=free
(x, Y_0, z)	v=0
(x, y, Z_{max})	w=0
(x, y, Z_o)	w=const (CDOF[2])

Where u, v, and w are the displacements in the x, y, and z respectively. A simplified analysis using simple averaging technique for a homogeneous material was used in this study to obtain the effective stiffness properties for our unit cell. The effective (overall) composite stiffness relates the homogenised stress within the material unit cell to the average strain over the unit cell.

Six different loading conditions were applied on to the unit cell to calculate stress averaging on the unit cell for each loading case. The average stresses were obtained by volumetric averaging of the effective unit cell's stresses over the unit cell volume

$$<\sigma>=\frac{1}{V}\sum_{e=1}^{Ne}<\sigma^e>V^e ,$$

Where: C^c is the effective (overall) composite stiffness, $<\sigma^e>$ average stress on an element, V^e Volume of element, V Total volume of the FE model, N_e Number of elements in FE model.

4. Results and discussion

Geometrical models representing the unit cell of IWHC and their parent textile reinforced composites have been built using the geometrical characterisation data (table 2) derived from experiments using Wisetex modeller the output of the latter has been transferred to the Inclusion and Cell modelling codes. FE models were built using Ideas-8 modelling task and by importing the geometrical data from Wisetex. The experimental and numerical findings are presented in Figure 3. Poissons ratio (v_0) was calculated using the inclusion model. All strength and stiffens results were normalised to a 45% fibre volume fraction.

Longitudinal tensile results show a trend in stiffness properties increasing with the increase in carbon content in the hybrid composite (Figure 4). The highest value was at the carbon composites (49.42 GPa), with its highest standard deviation (3.81 Gpa) among other composites. This could be due to carbon composites sensitivity to processing; especially to voids created in the wet lay up laminating. Stress strain curve showed linear behaviour up to samples breakage. Samples showed different modes of failure represented by Aramid fibres ductile breakage and looping (Figure 5a), carbon fibres brittle breakage (Figure 5c), while the C50 hybrid composite showed mixed mode of damage (Figure 5b).

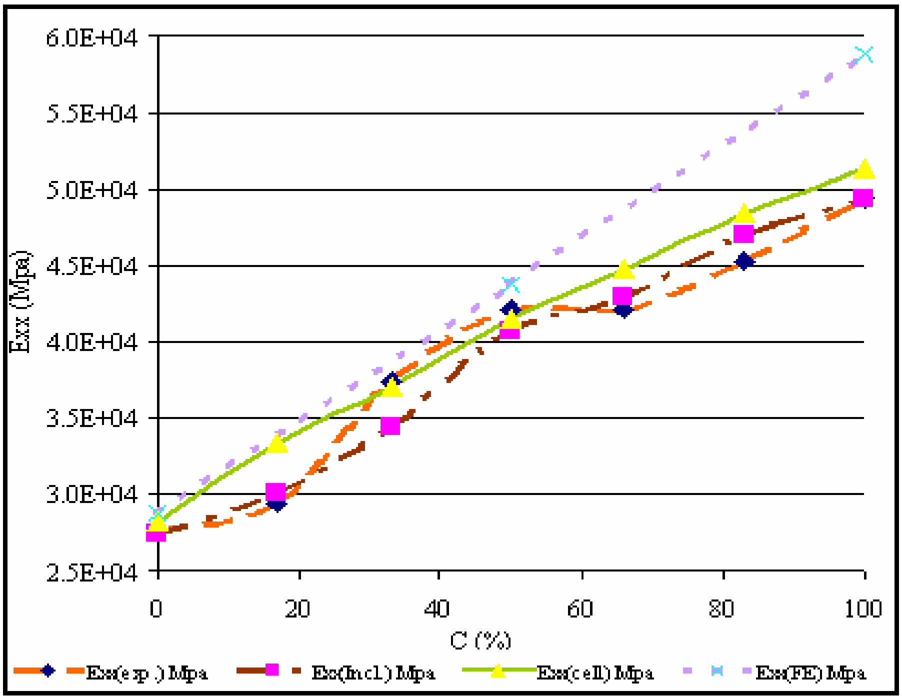

Figure 4: Experimental and analytical stiffness (Young Moduli) for different carbon content hybrid composites

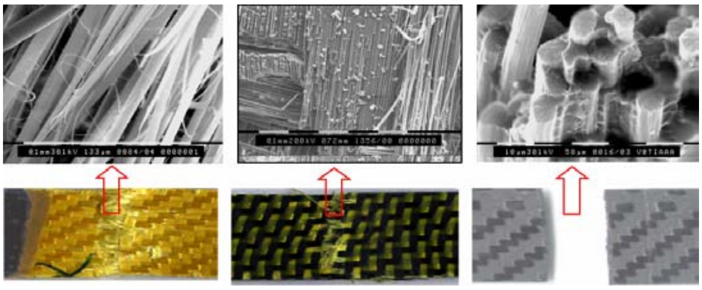
5a 5b 5c

Figure 5a, 5b and 5c: Different modes of failure in the aramid, C50, Carbon composites (5a, 5b, and 5c) tensile tested samples in 0° direction of loading

Matrix debris was found surrounding the deformed fibres. This indicates that the aramid fibres suffered substantial extension where energy has been absorbed in this form of damage. Poor bonding were observed at the fibres and their surrounding matrix. Also aramid fibres reduced in diameter and pulled out. While Carbon tensile samples under longitudinal tensile loading, showed interface failure represented by the transverse de bonding for the fibres in weft and a brittle fibre breakage for the fibres in warp with some extent of fibre pullout (Figure 5c). Mixed failure was found in the hybrid composites (Figure 5b).

The Bias tensile samples showed high deformation areas; where the sample narrowed significantly in the width at the central region (Figure 6). Also the composites showed high strain to failure (over 9.5%) in carbon composite compared to 0.9% in the 0° tensile tested samples. While stiffness and strength properties showed high anisotropy in all composites. Young's Moduli values were at their highest in the warp and weft directions (due to materials symmetry) but lowest values in materials bias direction. Non-linearity has been characterised in the stress-strain curve in all composites tested in the longitudinal tensile and the Bias directions. This is caused by de-laminations and matrix failure in carbon, while aramid composites suffered fibres buckling in addition to that failure.

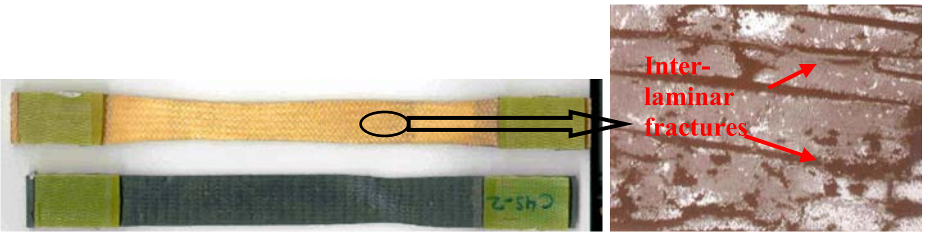

Figure 6: Carbon and aramid 45° tensile tested samples showed narrowing in sample's width. A microscopic image for the thickness of a failed carbon composite tested in tensile along the Bias direction (45°) revealed inter-laminar fractures

Stiffness properties showed high anisotropy in all composites (table 3). Young Moduli were at their highest values at the warp and weft directions (due to materials symmetry) but at their lowest values in materials bias direction. While in plane shear moduli and Poisson constants reached their maximum values at a 45° off axis orientation and they were at their lowest values in warp and weft directions (table 4).

Table 4: Poissons ratio using FEA, inclusion and cell models

	Composite	zy	yz	yx	xy	xz	zx
FEA	A	0.397	0.058	0.058	0.401	0.036	0.036
	C50	0.402	0.043	0.043	0.410	0.027	0.027
	C	0.406	0.036	0.036	0.416	0.023	0.023
Inclusion model	A	0.386	0.045	0.045	0.386	0.035	0.035
	C50	0.393	0.034	0.035	0.394	0.030	0.031
	C	0.373	0.029	0.029	0.373	0.028	0.028
Cell model	A	0.369	0.045	0.045	0.369	0.039	0.039
	C50	0.374	0.033	0.034	0.370	0.034	0.036
	C	0.371	0.029	0.029	0.371	0.031	0.031

The reasons for any deviations from the experimental results can be considered as follows:

By considering homogenised yarns properties we neglected the yarn's progressive micro-mechanical damage events (matrix cracking, fibre breakage, and de bonding), this resulted in an overestimation of the predicted elastic prosperities. Part of the error in the FE model can be attributed to the inaccuracies in yarn's shape description, especially in the out of plane co-ordinates of the paths. Despite this, it is clear that the yarn mesh in the FE model is capable of predicting the anisotropic behaviour of woven fabric composites, which also indicates that geometrical aspects like yarns shape, yarns cross section, and orientation are of a secondary importance in the tensile behaviour of hybrid composites.

Meso-mechanical results using the inclusion model have been affected by disregarding the □factor effects described by Huysman. This value depends on materials physical properties and yarns curvature. A recommended value $\pi/2$ (calibrated on a plain weave glass fabric) has been used in our calculation. Calibration procedure would be recommended to obtain accurate value to be used for this type of reinforcement. However, since the aim of this study is to validate the applicability of the generic inclusion method applicability to predict IWHC mechanical properties, only an evaluation of the results would be needed to achieve these aims.

These errors could be attributed to difficulties in describing the geometry and the properties of the constituents of the textile correctly. On the other hand, the fibres manufacturer did not provide transversal fibres properties. Fibres properties have been obtained from different literature resources. Such assumptions could contribute in the relative error in our predictions.

A draw back of the boundary conditions applied in our FEM is that it did not consider the far fields displacement (periodic boundary conditions). Periodic displacements boundary conditions are to be applied using constraint equations on pairs of nodes lying on the opposite unit cell faces, with the simulation tool available in IDEAS-8 this can be time consuming task. In addition their presence would increase the number of degrees of freedom associated with face's nodes and make to solve almost impossible. Therefore applying these periodic boundary conditions cannot be considered a generic method due to the difficulties associated in applying them. A draw back from using these simplified boundary conditions could develop reaction forces at nodes caused by the direct force application, leading to high-localised stresses, which results in misleading stress values. However FE methods, still allows the prediction of the effective stiffness properties using non-periodic boundary conditions, using the prescribed procedure in section (4.1). Further work would be needed to implement these boundary conditions by developing a program associated with IDEAS-8 to generate automatically pairs of corresponding nodes on opposite faces then coupling them with the appropriate constraint equations. This would improve the calculated stress and strain fields in the unit cell.

5 Conclusions

FE model for the IWHC showed that it could be a useful to estimate the composite behaviour, it allows consideration of non-periodic boundary conditions, and moreover it would give more insight view on the internal stress and strain distribution in

IWHC. However the difference in results for different mechanical properties, are caused by loss in geometrical details and due to simplifications made in applied boundary conditions. Stiffness properties showed high anisotropy in all composites. Fibre dominated elastic properties (e.g. on-axis moduli) are predicted with an acceptable accuracy but matrix-dominated behaviour, like shear properties are predicted with significant errors. Damage analysis using FE and photo-grametry strain mapping showed similarity in the strain repetitive patterns and values. Strain analysis was useful in predicting probability of strain to failure initiation in IWHC and in locating their locations in the unit cell. The damage analysis was supported by SEM and AE monitoring, which agreed with our FE analysis.

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