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EXPERIMENTAL CHARACTERISATION AND PREDICTION OF ELASTIC PROPERTIES OF WOVEN FABRIC REINFORCED TEXTILE COMPOSITE LAMINATES

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ABSTRACT

This paper first introduces the well-established analytical and numerical predictive methods used to calculate the elastic properties of woven fabric reinforced textile composite laminates. An experimental study follows where an E-glass plain woven fabric/epoxy composite laminate was manufactured and tested in order to measure the modulus of elasticity and yarn dimensions, and also to observe the typical damage patterns. Next, a state-of-the-art textile geometry modelling and a finite element analysis software was used in combination to predict the modulus of elasticity of the composite laminate using the experimentally determined yarn dimensions. Several numerical parameters such as voxel numbers, boundary conditions and element type were investigated to evaluate their effect on the predictions and the computational cost. Single layer representative volume element (RVE) with full integration formulation provided the closest prediction for the experimentally determined modulus of elasticity with an insignificant increase in computational cost. However, more representative damage patterns were observed with periodic boundary conditions and reduced integration formulation. It is recommended to use the latter parameters since they provide a more accurate representation of the physical behaviour.

Keywords: Woven fabric textile composites, Elastic properties, Fabric geometry modelling, Finite element analysis

1. INTRODUCTION

The adoption of fibre reinforced composite materials has been increased step by step from 3% in Airbus A320 to over 50% in Boeing 787, Airbus A380 and A350 over the past decades. Although the superior specific strength and stiffness properties of composite materials are being the leading features, this consistent increase is also based on the operational confidence established by extensive research efforts, advancements in the manufacturing techniques and relatively reduced material and manufacturing costs.

Two-dimensional (2-D) multi-directional fibre reinforced composite (tape) laminates are currently the dominant choice in primary load carrying aerospace structural parts mainly due to their exceptional in-plane stiffness and strength properties and good fatigue resistance. However, tape laminates suffer from relatively poor damage tolerance and low interlaminar strength as well as relatively high material and manufacturing costs [1].

Textile composites are being considered and developed as structural parts in aerospace industry as an alternative to the unidirectional tape laminates. “Textile” composites mainly consist of fabric preforms produced by textile forming technologies. They offer lower manufacturing cost, easy handling, near-net shape manufacturability, improved out-of-plane stiffness, strength and toughness at the expense of slight to moderate reduction in the in-plane stiffness and strength properties in comparison to the tape laminates [2].

A great challenge with the textile composites is directly related to their intrinsic fibre architecture. Elastic material properties and strength of the 2-D tape laminates can be predicted reasonably well with the analytical and numerical methods owing to their relatively simple fibre architectures with no

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significant undulations. However, the complex architecture of the textile composites complicates the prediction of their mechanical properties [3].

Woven fabric composites are an important class of textile composites. They are made by stacking the woven fabric layers which consist of interlaced warp and weft (fill) yarns directed along the length and the width of the fabric, respectively. Each yarn consists of a bundle of fibres where the number of fibres in thousands is used to characterise the yarn size. The fabric can be pre-impregnated (prepreg) with resin matrix or used in dry form. The prepreg layers can be cured in an autoclave such as in the case of tape laminates. The dry fabrics can be stacked and consolidated for example with the resin infusion process.

There are several predictive methods available for the elastic properties of woven composites. Most commonly used analytical and numerical methods are presented below.

1.1. Predictive Analytical Methods

The woven fabric geometry is defined with two geometric parameters (n_{fg} and n_{wg}) which define the interlacement order of the yarns in fill and warp directions. A warp yarn interlaces with every n_{fg}th filling yarn and a weft yarn interlaces with every nwgth warp yarn. A single parameter ng usually used when $n_{fg} = n_{wg}$. The fabrics classified according to ng are shown in Figure 1; plain weave (ng=2); left twill ½ (ng=3); four-harness satin (crowfoot) (ng=4); eight-harness satin (ng=8) [4]. The dotted lines over the fabric patterns show the “unit cells” which are the basic repeating patterns of the fabrics.

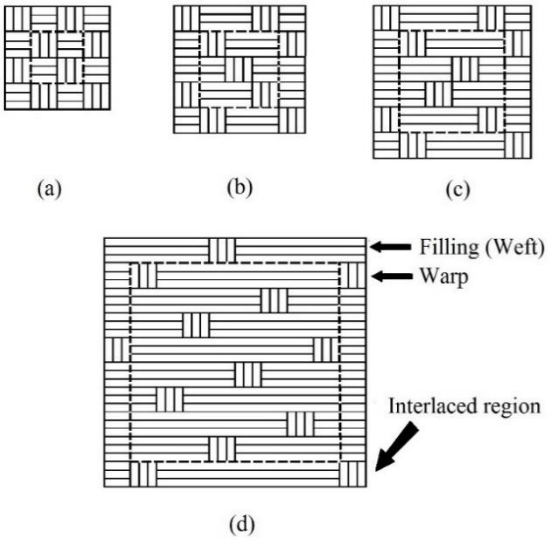


Figure 1. Examples of woven fabric patterns: (a) plain weave (ng=2); (b) left twill ½ (ng=3); (c) four-harness satin (crowfoot) (ng=4); (d) eight-harness satin (ng=8) [1]

Although different nomenclature and geometric definitions have been used, a plain weave composite is generally characterised by yarn spacing (a) in the warp and weft directions, warp and weft yarn filament counts (n), yarn packaging density (pd), fibre diameter (df) and overall fibre volume fraction (Vf). These given properties are used to determine the unknown properties of the composite such as yarn thickness (t), yarn cross-sectional areas (A), yarn crimp angle (θc) and yarn undulating paths which are required to model each yarn within a representative unit cell (RUC), see Figure 2 [5]. Analytical and numerical methods have been developed based on various representations of RUC of the textile architecture.

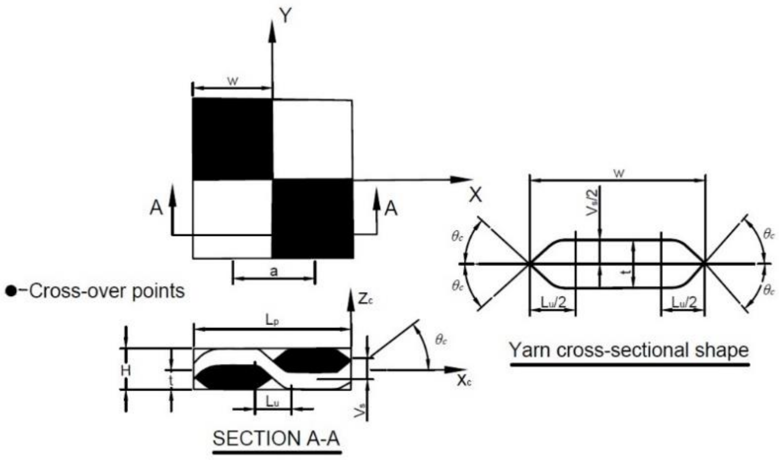


Figure 2. The Representative Unit Cell (RUC) geometry and notation for a 2-D plain weave composite [2].

Ishikawa and Chou [4, 6] developed three analytical models based on classical laminated plate theory in order to predict the elastic response and strength of plain and satin non-hybrid and hybrid woven-fabric composites: mosaic, crimp (fibre undulation) and bridging models. The mosaic model represents the woven structure as an assembly of asymmetric cross-ply laminates where the fibre continuity and crimp was ignored.

The crimp model was proposed in order to overcome these shortcomings. The undulation shape of the fibres was represented by several parameters. The fill and warp yarn shapes were expressed by piecewise sinusoidal functions and the laminated plate theory was assumed to be applicable for each infinitesimal piece of the yarns. The pure matrix region was also taken into account discretely.

Based on the mosaic and crimp models, a bridging model was developed for satin weaves ($n_g \geq 4$) which separates the interlaced region of the unit cell from the surrounding "cross-ply" regions. Since these models are based on classical laminated plate theory, 3-D properties of the laminates cannot be predicted.

Naik and Ganesh [7-9] developed a closed form analytical method for thermoelastic analysis of 2-D plain weave composites. Unlike the previous models of Chou and Ishikawa [4], they considered the yarn undulation and continuity in both warp and weft directions by using a unit cell. The sections of the unit cell were divided into straight and undulated warp and fill regions and pure matrix region in order to simplify the calculations. The effective elastic properties of the small pieces were summed up to give the overall elastic properties using the classical lamination theory.

Scida et al. [10] developed a classical lamination theory based analytical model (MESOTEX) in order to predict the elastic properties and strength of plain, satin and twill-weave fibre composite materials. The model is based on the crimp model of Ishikawa and Chou [4] and is quite similar to that of Naik and Shembekar [7]. The undulated portion of each warp and fill yarns in the unit cell was represented by a sinusoidal curve and divided into infinitesimal portions. Overall elastic properties were calculated by summing up the stiffness matrices of these small portions.

1.2. Predictive Numerical Methods

Whitcomb and co-workers devoted a considerable effort on the development of finite element models for textile composites [11-19]. A detailed finite element stress analysis of plain woven fabric composite, probably the first 3-D analysis, was performed in Ref. [18] with a specific aim to show the effect of yarn waviness on the effective moduli, Poisson's ratios and the internal strain distributions. The yarn elastic material properties were assumed to be the same as for unidirectional tape prepreg material. The resin was assumed to be isotropic. While the out-of-plane shear modulus was increased, effective in-plane moduli were reduced linearly with increased waviness. The effect was more significant in the loading direction modulus which was partly attributed to increased resin volume fraction with the increased yarn waviness.

Whitcomb and Srirengan [15] studied the effect of various finite element characteristics on the progressive failure behaviour of plain woven AS4/3501-6 graphite/epoxy composites using 3-D finite element analysis. The variables under a uniaxial loading condition were the quadrature order, mesh density, material degradation model and the tow waviness. The unit cell with and without matrix pockets are shown in Figs. 3 (a) and (b). The advantage of the model symmetry in the loading direction was used in order to simplify the analysis as shown in Figure 3 (c).

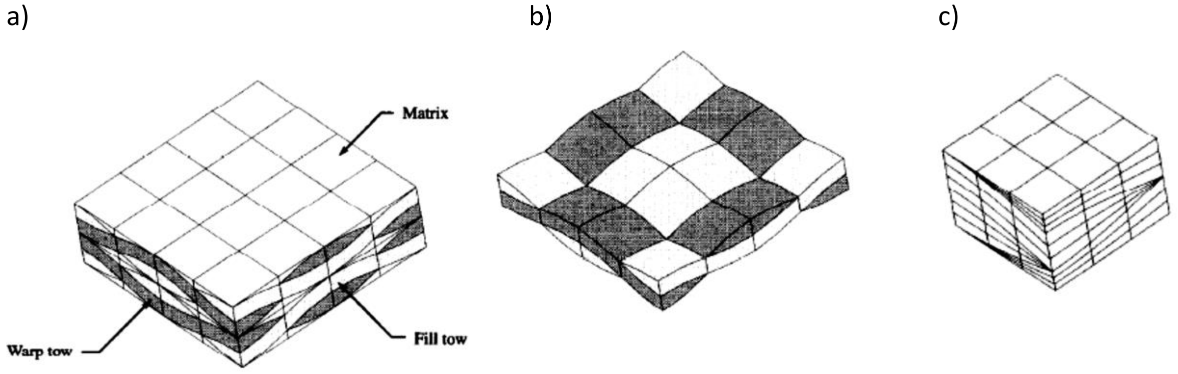


Figure 3. Schematic views of a plain weave textile composite: a) full unit cell, b) unit cell with matrix pockets removed and c) 1/32th of a unit cell with a selected mesh density of 108 elements and 634 nodes [5].

The tows were modelled with an assumed lenticular cross-section along a sinusoidal path. The tow waviness had a significant influence on the strength predictions as expected. The number of the Gauss points had a little effect on the stress predictions up to the damage onset where the predictions started to deviate considerably. Reduced tow waviness not only increased the strength but also retarded the damage initiation with respect to the peak stress. It was shown that the tow waviness affects the strength predictions as well as the mode of damage since the stress components responsible for the damage was changed. Although no experimental validation was attempted, it was emphasized that certain approximations and assumptions were unavoidable when modelling the damage in textile composites based on the variations of the predictions.

A displacement based finite element (referred to as macro element) was developed by Whitcomb et al. [11] within a single element which takes the microstructure of the textile composite into account. Although the global deformation behaviour was predicted with a reasonable accuracy, the internal stress predictions within the macro model were inaccurate due to the simplifying single field assumption. A global/local modelling strategy was suggested in order to obtain better predictions where the macro and conventional elements should be used for the global and local analysis, respectively.

A mode based global/local analysis method was proposed by Srirengan et al. [17] for 3-D stress analysis of plain weave textile composites. Homogenized material properties were used for the global analysis where only a few elements were implemented for meshing the whole model. A local analysis was then performed which took the individual tows and the matrix into account in order to obtain a detailed stress distribution. Despite the significant errors when linear modes were dominant, the method was found to be more efficient in terms of computational requirements in comparison to conventional analysis methods.

In this study, rigorous mechanical testing and internal structure observation procedures were used to characterise a woven fabric reinforced/epoxy composite plate. The novelty of the paper is the implementation of state-of-the-art geometry modelling software in combination with a widely used finite element software, Abaqus in order to predict the mechanical properties of the composite plate. The assumptions and modelling options that ensured a satisfactory correlation with experimentally obtained data were presented. This will be beneficial for the researchers and engineers for numerical modelling of the textile reinforced composite materials.

2. EXPERIMENTAL STUDY

2.1. Measurement of Elastic Properties of A Plain Woven Fabric Reinforced Composite Laminate

E-glass plain woven fabric/epoxy material system was manufactured with vacuum assisted resin transfer moulding (VARTM) technique. The dry woven fabric has 500 g/m^2 areal weight made of continuous glass fibre bundles. An epoxy resin, Hexion LR160, was vacuumed into eight stacks of dry plain woven fabric with the vacuum pressure of approximately -700 mmHg at room temperature. Overall fibre volume fraction of the laminates was found to be 56% using the burn off procedure of ASTM D-3171 standard [20]. After the curing was completed, the GFRP plates were cut into specimen sizes (see Table 1) with a carbide tool. A schematic drawing and a photograph of the tensile specimen is shown in Figure 4.

Table 1. Dimensions of the tensile test specimens

Specimen length (L)	250 mm
Specimen width (w)	25 mm
Specimen thickness (t)	3 mm
Grip length (L_{grip})	50 mm
Gauge length (L_{gauge})	150 mm
Extensometer gauge length (L_{extens})	50 mm

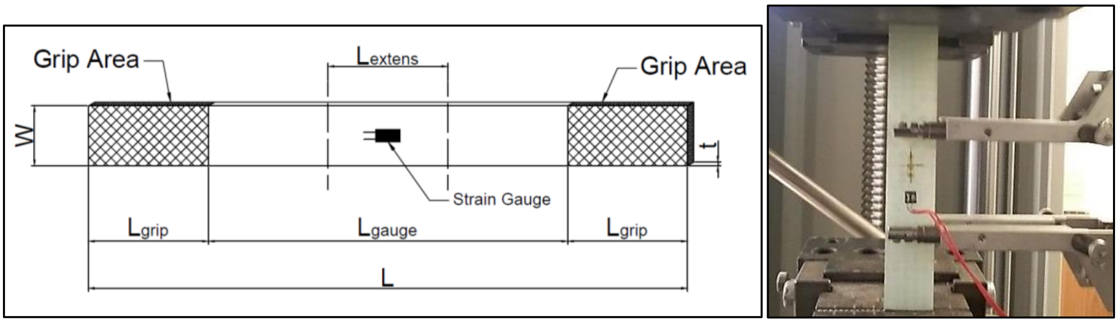


Figure 4. Schematic drawing and a photograph of a composite tensile test specimen mounted on the testing machine.

Due to the nature of plain woven fabrics, in-plane elasticity moduli were assumed to be equal in warp and weft directions. Therefore, the modulus was measured only along the loading direction with a Zwick-Roell mechanical testing machine. An extensometer, as shown in Figure 4, was used to read the strain data. The extensometer gauge length was set to 50 mm at the mid-span of the specimens. A 5 mm uniaxial foil strain gauge, BFLA-5-5 of Tokyo Sokki Kenkyujo Co., was also bonded to one of the specimens along the loading direction. Specimen preparation and the tensile tests were performed following the ASTM D-3039 standard [1]. The elasticity modulus was determined from the slope of the linear stress-strain curve between 0.1% and 0.3% extension levels. The tests were conducted at room temperature with a constant crosshead speed of 2 mm/min. The stress-strain curves (three specimens with extensometer and one specimen with bonded strain gauge) are given in Figure 5. The measured elasticity modules were listed in Table 2.

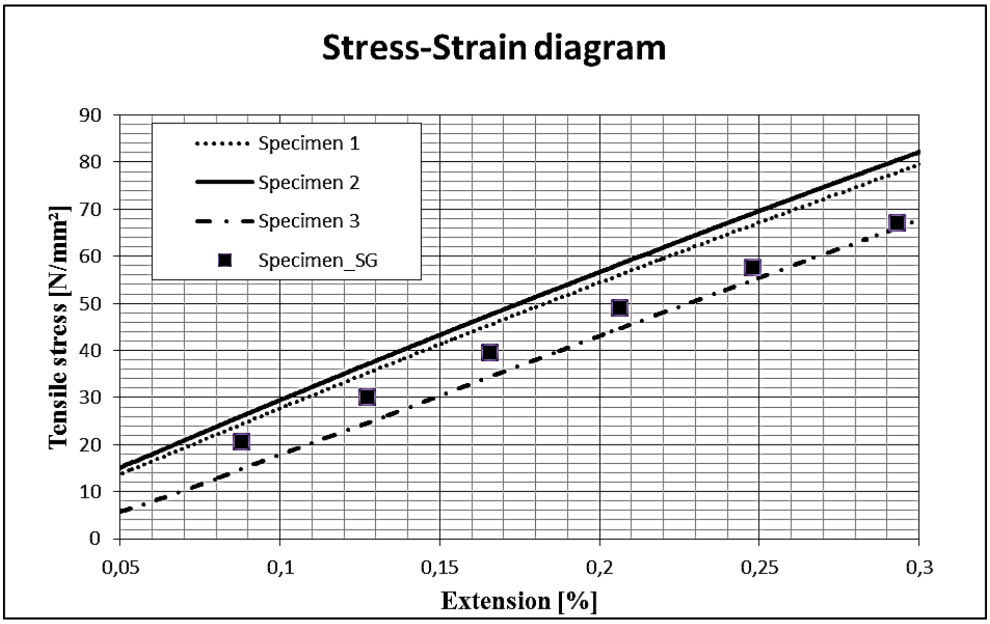


Figure 5. Stress-strain curves of the specimens

Table 2. Calculated moduli of elasticity

	Specimen Code	**Elasticity Modulus (GPa)**	**Mean Value (GPa)**
Extensometer	Specimen 1	25.89	25.75, c.v. (2.61%)
	Specimen 2	26.34	
	Specimen 3	25.02	
Strain Gauge	Specimen_SG	23.52	23.52

2.2. Measurement of Geometrical Inputs Required for the Numerical Model

A numerical tool will be used in the following sections in order to predict the elastic modulus of the woven fabric composite laminate. The numerical model requires geometrical inputs such as bundle width, thickness and spacing between the yarns. These inputs were obtained by optical micrographs of the cross sections of the specimens. The specimens used for optical investigation were moulded with the same resin system of the composite laminates. The specimen surfaces were polished with sandpaper in multiple steps and etched for capturing better images. A cross-sectional view of the woven glass/epoxy specimen with the nominal microstructural dimensions is shown in Figure 6, where the mean values of five optical measurements were found as follows; yarn spacing a=5.11 mm, yarn width w=4.72 mm and yarn thickness t =0.375 mm.

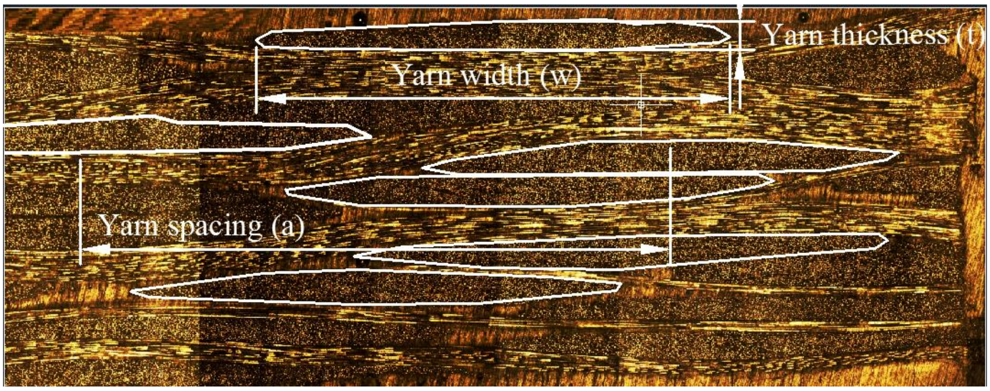


Figure 6. Representative cross-sectional view of glass woven fabric epoxy laminate

3. ESTIMATION OF ELASTIC PROPERTIES OF THE PLAIN WOVEN FABRIC LAMINATE

The elasticity modulus of the woven fabric laminate was estimated using TexGen modelling software and Abaqus finite element (FE) software together. TexGen is an open access, 3-D geometry modelling software package for textile composites developed at the University of Nottingham [21] whereas Abaqus is a general purpose FE software. It is possible to model various types of textile composites with TexGen in the final state (the manufacturing process is not taken into account) including woven, non-woven, braided and knitted fabrics. The yarns are modelled as simple approximate solid volumes instead of individual fibre modelling which would be too expensive in terms of modelling effort and computational requirements.

Geometry modelling is an important initial step for studying the mechanical behaviour of textile composites. Several measurements such as yarn spacing, fabric thickness and yarn width should be obtained from the actual fabric structure in order to create the TexGen model. The unit cell models then can be exported to Abaqus FE analysis software for stiffness and strength predictions. There are several export options available: IGES, STEP, Surface Mesh, Volume Mesh, Tetgen Mesh, Abaqus Dry Fibre File and Abaqus Voxel File. Once the textile model is imported into the Abaqus, appropriate boundary conditions should be defined separately for the yarns and the matrix. Then, the elastic properties of the textile unit cell can be determined from the applied load-displacement curves of the models. The matrix may be represented as elastic-perfectly plastic material whereas the yarns may be modelled as transversely isotropic material such as unidirectional tape laminae.

Figure 7 shows the fabric architecture created by TexGen software according to the parameters given in Figure 6 (yarn spacing a=5.11 mm, yarn width w=4.72 mm and yarn thickness t =0.375 mm).

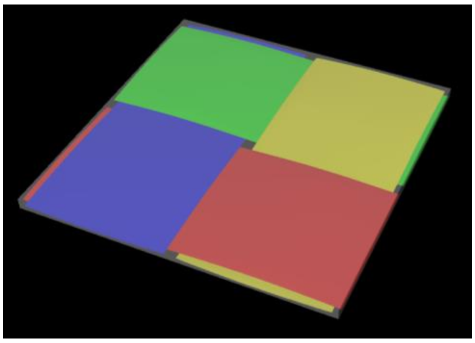


Figure 7. Plain woven fabric geometry of E-glass fibre/epoxy laminates created using TexGen (warp yarns: blue and yellow, fill yarns: red and green).

Once the geometry is created, it is necessary to assign elastic material properties to each yarn and matrix in order to evaluate the overall elastic properties of the fabric composite. The yarns are represented as transversely isotropic composite layers whereas the matrix material is assumed to have a linear elastic behaviour. The modulus of elasticity of the E-glass fibres and epoxy matrix are 72.0 GPa [22] and 3.5 GPa [23], respectively. The Poisson's ratio of the fibres is 0.22 while it is 0.35 for the matrix material. Experimentally determined overall composite and calculated corresponding yarn fibre volume fractions are $\boldsymbol{V_f^0}$=56% and $\boldsymbol{V_f^s}$=84%, respectively. The well-known rule of mixtures was used to estimate the transversely isotropic elastic properties of the yarns. Predicted elastic properties are tabulated in Table 3.

Table 3. Elastic properties of UD laminae using the rule of mixtures

Material	$\boldsymbol{E_L}$ (GPa)	$\boldsymbol{E_T}$ (GPa)	$\boldsymbol{G_{LT}}$ (GPa)	$\boldsymbol{\nu_{LT}}$	**V$_f$**
E-Glass/epoxy	62.40	18.40	6.93	0.24	0.84

Abaqus voxel files were created using different voxel numbers in X (fill), Y (warp) and Z (thickness) directions. The voxel numbers used are as follows: Model 1 (X: 50; Y: 50; Z: 20), Model 2 (X: 50; Y: 50; Z: 30), Model 3 (X: 80; Y: 80; Z: 30). Voxel numbers indicate the number of the elements created in the FE model. Therefore, various voxel numbers were used to define an optimum FE model in which the acceptable solution time provides accurate elastic property estimation. The element type used was the reduced integration linear cubic element C3D8R. During the exporting process of the voxel files from the TexGen software, material continuum option was selected for the periodic boundary condition enforcement.

The results obtained with an Intel I7-6700 CPU @ 3.41 MHz, 16 GB RAM computer are given in Table 4 for different models along with the experimental data. Considering the slight difference between the predictions, it is clear that Model 1 can be used for the solution in terms of accuracy and the solution time efficiency. Model 1 also was chosen for further parametric study performed for the E-glass/epoxy material. Although the properties were overpredicted by 5.19%, the agreement is acceptable considering the high experimental scatter for textile composites.

Table 4. Comparison of predicted and experimental elastic properties of E-glass/epoxy plain woven fabric composites

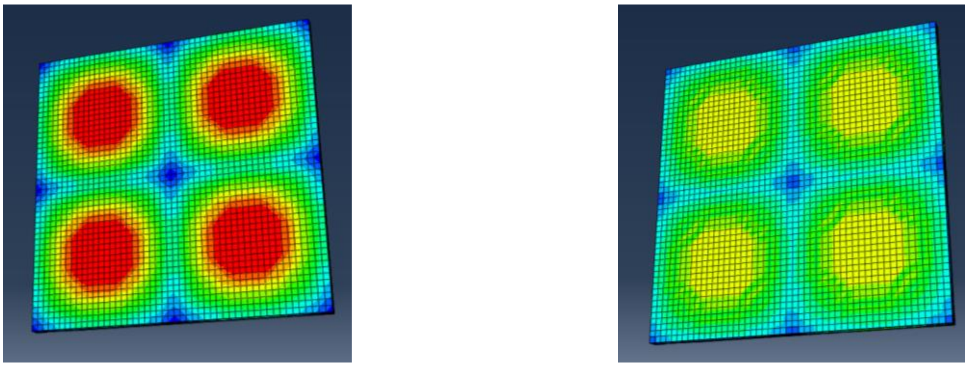
Model	**E$_L$ (GPa)**	**Error (%)**	**Solution Time (Min)**
Model 1	27.16	5.19	3.6
Model 2	27.32	5.75	10.2
Model 3	27.23	5.44	46.6
Experiment	25.75	-	-

There are several options/alternatives to export the TexGen model into the FE software depending upon the boundary conditions and layup construction of the composite laminates and also the numerical solution procedure and element type of the model. The analyst should have a sound understanding of each option on the solution accuracy. For example, material continuum option allows solving the elastic properties in 3-D coordinate system while single layer representative volume element (single layer RVE) assumes plane stress conditions. The element types C3D8 and C3D8R are eight node solid brick elements with full and reduced integration formulations, respectively. A comparative study was conducted to give an insight into the influence of these options on the elastic response of the laminate. The results are listed in Table 5 for Model 1.

Table 5. Comparison of different solution strategies for E-glass/epoxy plain woven fabric composites

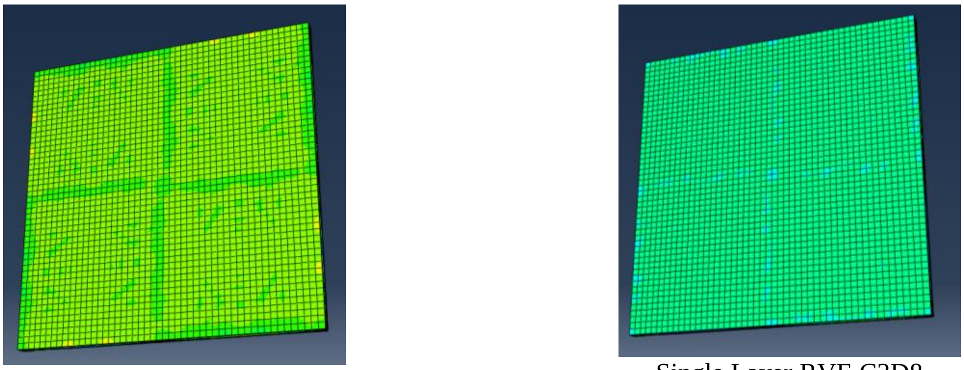
Output Type		**E_{11} (GPa)**	**Error (%)**	**Solution Time (Min)**
Periodic B. C.	**Element Type**			
Material Continuum	C3D8R	27.16	5.19	3.6
Material Continuum	C3D8	27.32	5.75	3.6
Single Layer RVE	C3D8R	25.32	-1.7	3.6
Single Layer RVE	C3D8	25.47	-1.1	3.7
Experiment		25.75	-	-

Although this paper focuses on the elastic response of a woven fabric composite laminate, a qualitative analysis on the stress gradients of the FE models can provide useful information on the damage and failure behaviour of the laminates. Figure 8 illustrates the stress distributions within the unit cell of the laminate as a function of various boundary conditions and material integration options along with an image of a damaged specimen.



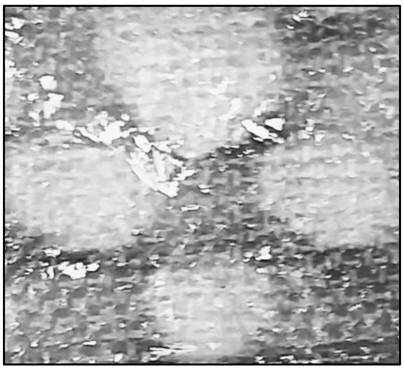
Mat.Cont. C3D8R

Mat. Cont. C3D8



Single Layer RVE C3D8R

Single Layer RVE C3D8



Damaged specimen (lighter areas indicate the damage locations)

Figure 8. Comparison of different FE stress distributions and a part of a damaged specimen (Red colour depicts high stress areas, blue colour depicts low stress areas for the FE images).

The experimental damage locations are consistent with the high stress intensity zones of the FE solution when the Material Continuum export option is used. Since the Single Layer RVE approach assumes plain stress conditions (through the thickness stresses are ignored), a uniform stress distribution over the undulation regions is appeared which is not consistent with the experimental observations. This comparison indicates that the Material Continuum approach correlates better with the experimental observations.

4. CONCLUSIONS

A study was presented on the elastic response of the plain woven fabric reinforced textile composite laminates. Implementation of analytical and numerical models for the elastic response of the textile composites requires more effort than the unidirectional tape laminates. In addition to the elastic properties of fibre and matrix material system, a careful destructive sectioning and optical investigation is necessary for the determination of the geometrical yarn properties in order to predict the elastic behaviour.

There are various geometry exporting options are available when using the TexGen software and several parametric analyses were performed to shed some light on their effect on the elastic response and damage mechanisms. This may be beneficial for the analyst and engineers dealing with the textile composite materials. Furthermore, some assumptions relating the geometrical structure of the yarns and laminates were made in the geometry modelling software such as perfect yarn geometry, constant yarn cross-section and periodical undulation of the yarns. In reality, however, geometrical imperfections may occur in the microstructure as a result of the manufacturing process. Therefore, the assumptions may cause some deviations between the experimental and numerical results. Nevertheless, the agreement is acceptable considering the high experimental scatter of the textile composites.

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