Serbian Tribology Society

SERBIATRIB '19

16th International Conference on Tribology

Faculty of Engineering University of Kragujevac

Kragujevac, Serbia, 15 – 17 May 2019

COMPUTER AIDED GEOMETRIC DESIGN IN MODELLING OF 3D TEXTILE COMPOSITES

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Abstract: *Orthogonal three-dimensional textile composite was evaluated by using numerical simulation. Three-dimensional (3D) geometry models were created (angle interlock and layer to layer), with 48 % and 53 % overall volume fractions. Warp, weft and binder were adjusted according to the yarn spacing, width, and height. Finite element numerical simulation was realised by using multistep linear static test for general behaviour. Both models were evaluated based on the calculated stress and strain values. Internal yarn architecture and overall volume fractions both have significant influence on the mechanical behaviour of the composite.*

Keywords: *Textile composite, fiber reinforcement, Computer-aided geometric design, CAGD, FEM modelling, Stress, Strain.*

1. INTRODUCTION

Composite materials represent a combination of two or more phases that usually have different physical and mechanical properties at micro and macro scale. Altogether different materials combined together within composite structure, usually exhibit distinctively different properties than each of the constituents. Composites can be made with different structural shapes and sizes of reinforcements within the matrix, such as particulate inclusions, fibers or hybrid composites with several types of reinforcements. Textile composite, or laminate composites with different directions of laminates combinations, have emerged as attractive materials due to their application in aerospace, marine, transportation, and construction industries [1, 2]. They comprise yarns, which are anisotropic in nature and have lower modulus than fiber materials. Traditional laminated composites involve high labour cost and can exhibit delamination which can limit their application [2]. Development and selection of material combination from a wide range of composite structures is complex process. One current trend in textile engineering is to develop advanced composites using low cost, "out of autoclave" (OOA) manufacturing techniques. Instead of processing route that involves industrial autoclave, OOA provides material curing, desired fiber content and voids elimination via other techniques without use of autoclave (vacuum, pressure, or heat). The focus is to create advanced weaving architecture [7].

Efficient methods in design of composite structures engage computer modelling, simulation and numerical analysis of loading and structure responses in terms of resulting mechanical properties. Some of the techniques like Computer Aided Geometric Design (CAGD) that deals with mathematical description of shapes have been used in research of such structures. Design of 3D volumes aimed at 2D and 3D textile structures have been studied [1]. In combination with numerical simulation, development of textile composite structures can be efficiently supported. Modelling software is capable to create different 3D models by variations of weave type and yarns. Fabric compaction and yarn waviness are very important for final deformation properties of the composite and their overall mechanical properties [4, 5]. Additionally, three-dimensional (3D) printing is an additive manufacturing process that can rapidly fabricate samples of different geometries and structures, in order to experimentally study influence of different geometrical design on composite behaviour [11]. Numerical simulation is also powerful technique to study the influence of structural changes within the composite structure, on its mechanical behaviour. Usually, for 2D textile composites, idealised cells are applied in finite elements modelling (FEM) to determine stress – strain response. However, in case of 3D composite structures, such approach showed rather large differences from real cases and accordingly other approaches to finite element analysis (FEA) have been tried, such as voxel-based FEA or continuum damage model [3]. Voxel-based finite element meshing use labeled voxel information, such as computer tomography (CT) scan images, or some other digital images, and convert it to a finite element. Definition of the label is directly linked to different constituent materials within composite. That way, 3d volume model can be created that has close resemblance to the real material structure. Continuum damage models, for fiber reinforced composites, have been developed focused on the onset of intralaminar failure and its evolution until structure collapse, as well as the governing failure mechanisms.

Multi-scale modelling also has been proposed for the investigation of textile composites, such as based on Voronoi tessellation [6]. Homogenisation models that are often used for the characterisation of composites are not well suited for textile composites where geometry and internal architecture governs the stress and strain responses [6, 7]. Mechanical properties of the woven composites with complex 3D structures are significantly influenced by the distribution of different regions within the composite, such as the regions with increased resin content, or waviness [7]. Zones with binding sites represent initiation sites for damage, under all loading conditions, for all woven composites [7]. Different numerical simulation approaches provide different degree of similarity to real mechanical responses of textile composites. Idealised geometry is the most rapid way to predict internal structural behaviour. However, more complex methods, such as Digital Element Method which is focused on compaction process and analytical method that consider undulation of fill, warp and binder yarns, provided better geometry prediction [8]. Resulting elastic properties for all these approaches were similar. Architecture of reinforcements can be observed at micro-scale (fibers and matrix), meso-scale and macro-scale (usually considered as homogenous material) [9].

Three-dimensional modelling allows monitoring of friction and wear of fibers at multiscale level [12]. Computer Aided Geometric Design (CAGD) enabled investigation of different combinations of matrices and reinforcement material in order to obtain composites with the best tribomechanical characteristics, both at micro and macro level [13].

This paper deals with the design of three-dimensional textile composite with different volume fractions in two different geometrical variations. Numerical simulation, by using finite element method (FEM) was realised to obtain stress-strain responses. First model in

3d weave type was created based on angle interlock geometry, with 48 % overall volume fraction. Second model was created in layer to layer format, with 53 % overall volume fraction. Both of the 3D models were simulated under compressive loading. For numerical simulations, simple linear static set was performed with multi set options by using the laminated composite modelling concepts. Open source software TexGen was used for the design and development of three dimensional geometrical model. FEMAP with Nastran (structural package) software was used for the conversion of partial differential equations into finite element code.

2. GENERAL TYPES OF TEXTILE COMPOSITES

General types of textile composites, with their properties are described in Table 1. Textile composites have arrangement of weft, warp and binder sets, as shown in Fig. 1.

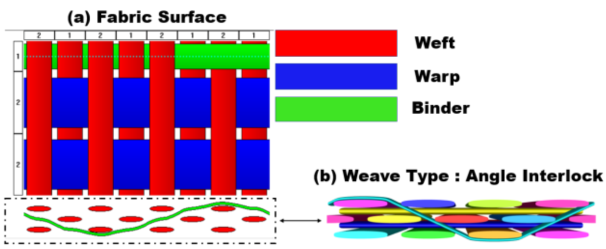

Figure 1. Schematic Representation of orthogonal 3D Woven Fabric Showing (a) Unit cell with tessellation; (b) 3D Weave type: Angle Interlock

They formed tessellations with proper sequence depending on the composite type. Figure 1 illustrates the orthogonal 3D woven fabric in angle interlock form. This model was created in open source software called TexGen. Spacing, width, height, and ratio of binder yarn were set according to real case properties.

Table 1. General types of textile composite and their main properties [1-4]

Type	**Woven**	**Braided**	**Knitted**	**biaxial**
Main property	- High delamination, resistance	- High Impact resistance	- Elastic, high productivity, low cost - Different types of geometric structures can be made	- Good Quality - Damage tolerance - Good peel strength - Reduced delamination
Angle	- Warp and weft yarns are oriented at 0 and 90 respectively. - Characterised by the repeating pattern of interlacing in warp and weft yarn direction	- Yarns interlacing is not set at 0 and 90 degree - Many forms can be made; one of yarn is set in one direction at some angle and the other half is in opposite direction		Made in three directions: - One in vertical direction (Weft) - Two in diagonal (warp) - 0 and 60 degree
Properties of simple 2D, plain, twill, satin weaves				
Advantages	- Balanced and unbalanced weaves - Open and closed packing - High out of plane strength - Good strength - Anisotropic stability	- Suitable for near net shape structure - Useful in cross sectional shapes such as nozzles, cones	- Low level of fiber packing density - High extendibility	- Quasi Isotropic at macro scale
Drawbacks	- Lower extendibility - Lower deep molding	- Low fiber fractions - Decreased in-plane mechanical properties	- Brittle fiber due to lot of twisting during knitting; may break easily	
Processing	- Vacuum injection process for thermoset matrix - Hybrid yarn technique for thermoplastic matrix	Made by orthogonally interlacing set of yarns	- 3D printing based on geometry model	Warp, weft and binder yarns are stitched together by chain stitch

3. NUMERICAL SIMULATION

Accuracy of modelling is based on material model and element geometry. TexGen software can be used to create 2D and 3D weave model. Unit cell can be assigned to the yarn in a number of different ways. In this work, TexGen software was used for the design of two different three-dimensional weave patterns (Table 2).

Table 1. Parameters of 3D weave pattern model

Parameter	Weft yarns	Warp yarns	Binder yarns
Yarns	4		
Number of yarns layers	3		
Yarn spacing	1	1	0.5
Yarn width	0.8	0.8	0.4
Yarn height	0.1	0.1	0.05
Power ellipse section power	0.6	0.6	0.6
Total number of yarns in warp direction	3	-	-
Ratio of binder yarns	1	-	-

Two different weave models were created, with properties given in Table 2: 1) angle interlock and 2) layer to layer. In case of angle interlock, binder goes in a fixed pattern from top to bottom. Number of weft yarns and weft layers are linked. In case of layer to layer, binder yarn is in stack whereas binder path is selected interactively. Damage and failure behaviour of 2D woven composites have been investigated by using multiscale progressive modelling [10]. TexGen software can create voxel mesh, comparable to the finite element mesh in terms of elastic properties, and local stress field evaluation [9]. First, STEP file was exported from TexGen software and further processed in FEMAP software using the meshing toolbox. As stated above, two varied geometrical model, Angle interlock with 48 % overall volume fraction and Layer to layer with 53 % overall volume fraction, were simulated under compression. Element size was restricted to 0.186, with a total of 10863 and 308892 solid tetrahedral parabolic 10 Node elements, assigned to both models. Both models were simulated with multi step structural static analysis and properties are given in Table 3, as implemented in X, Y, and Z directions. 3D orthotropic material orientation was assigned to the geometry.

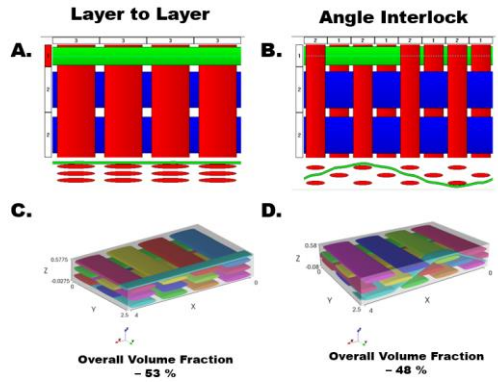

Figure 2. Schematic Representation of textile Composite in 2-Dimensional vie: A) Layer to Layer Format, B) Angle Interlock; and in 3D view: C) overall volume fractions of 53% and D) overall volume fractions of 48%

Linear stress analysis of 3D textile laminate composite was done. At the beginning of the numerical simulation, layup creation was done, followed by generation of the second layup for layers definition. Afterwards, mesh fitting was done and linear static test was realised to obtain stress – strain values. Geometry scale factor was set to mm scale at the beginning of the numerical simulation. 3D orthotropic material was adopted.

Table 2. Table of material properties for constituents and yarn [3]

	E_{11} (GPa)	E_{22} (GPa)	$V_{12} = V_{23}$	V_{23}	$G_{12} = G_{23}$	G_{23} (GPa)	S_{11} (MPa)	S_{22} (MPa)	$S_{12} = S_{13}$ (MPa)	S_{23} (MPa)
Carbon Fiber	238	13	0.20	0.25	13	6	4620	-	-	-
Epoxy Resin MVR 444	3.1	3.1	0.35	0.35	1.2	1.2	77.6	77.6	61.5	61.5
Yarn	167	8.1	0.24	0.37	4.5	3.0	3234	36.4	53.8	61.5

Density, modulus of elasticity in respective directions, and shear modulus were defined as given in Table 3. Poisson's ratio was taken from FEMAP material library for materials given in Table 3. Warp, weft and binder were distinguished in the modelling by giving the upper, lower and middle name with varied thicknesses at different angle starting from 0 – 45 degrees. FEMAP has the possibility to create the laminate's equivalent properties, number of layers and thickness related to plane properties which are usually bending and flexural properties. After sorting out the layers position and thickness, symmetric option was used. Similar approach was applied for the reinforcement fiber by adjusting the thickness and angle. For material orientation direction, Cartesian coordinate system was used. The Nastran bulk data was set to small field.

Upper surface of the geometrical model was loaded with 50 N load, as shown in Fig. 3. Bottom surface was fixed without any translational and rotational degrees of freedom.

Layer to layer and angle interlock geometrical models were evaluated based on the numerical values of stress and strain. Maximum shear stress and maximum principal stress contours, for layer to layer and angle interlock geometrical models are shown in Fig. 4. Model with 53 % volume fraction experienced higher magnitude of stress - strain values in X, Y and Z directions respectively. This is resulting from the amount of fibers and yarns within the structure that increased capability for extension in comparison to model with 48 %. Overall maximum shear stress showed similar behaviour in XY, YZ and ZX directions.

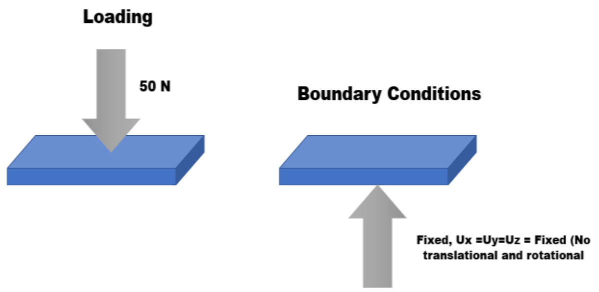

Figure 3. Loading (left) and boundary conditions (right) during uniaxial compressive testing

Results of stress – strain numerical calculations are shown in Fig. 5. Strain as the function of stress is shown for different volume fractions. It can be seen that the highest stress was exhibited for 48% volume fraction.

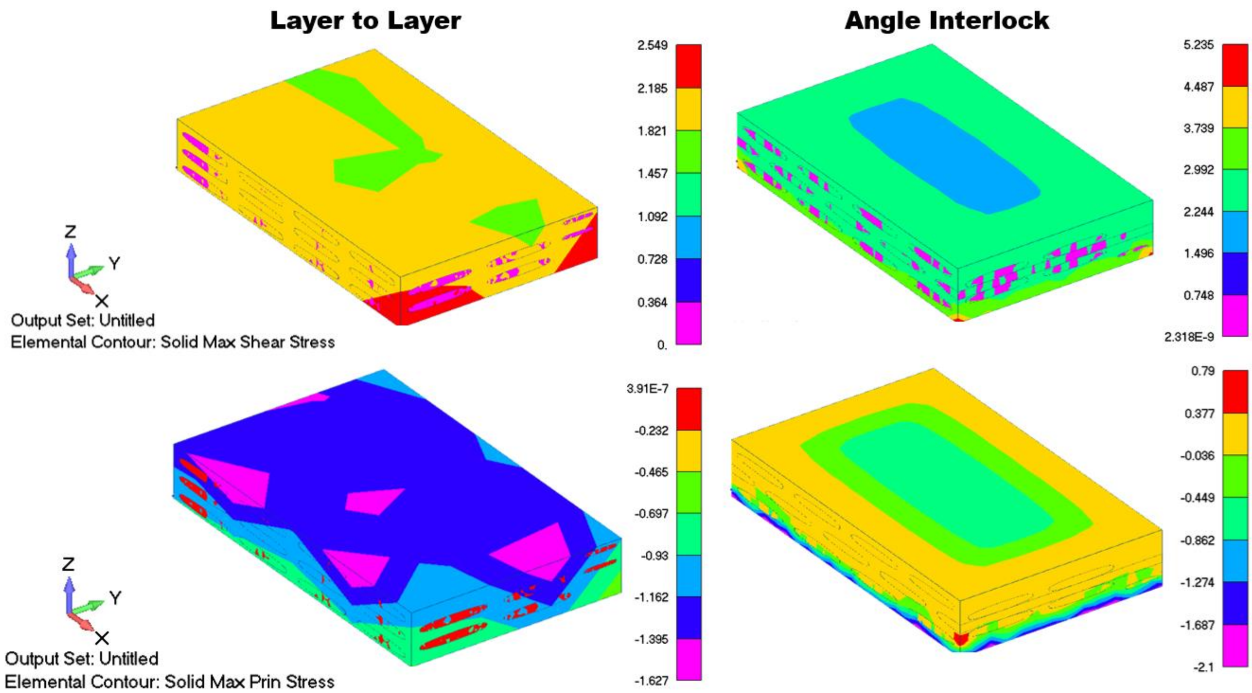

Figure 4. Upper row shows maximum shear stress contours [MPa] for layer to layer and angle interlock geometrical models. The bottom row shows maximum principal stress contours [MPa

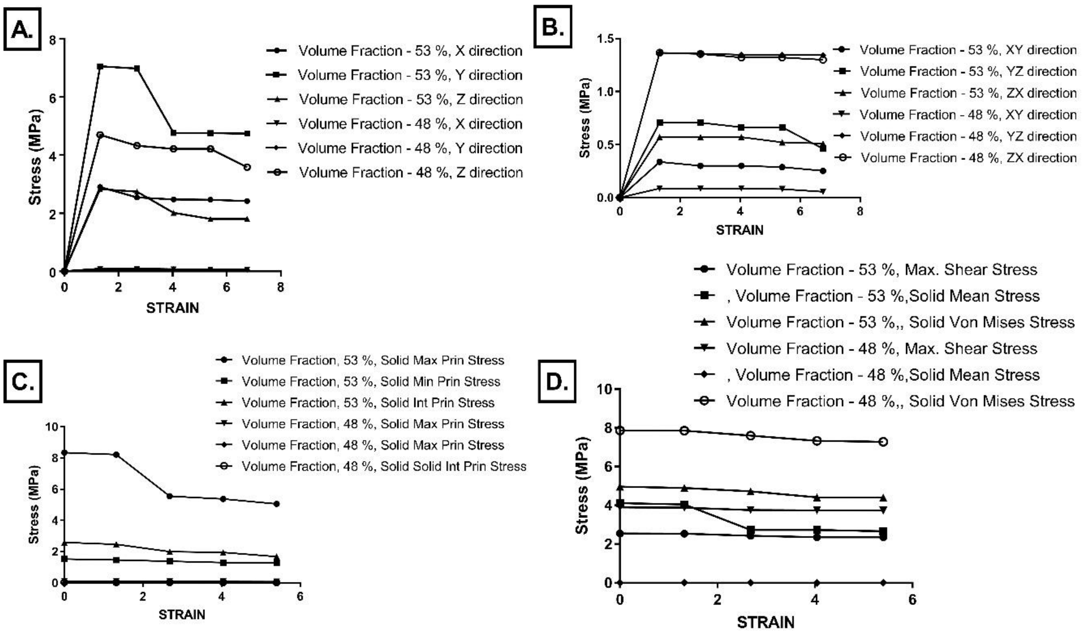

Figure 5. Stress - strain curves in: A) X, Y, Z directions and B) XY, YZ and ZX directions; C) Maximum, minimum and solid principal stress; D) Maximum shear, mean, and Von Mises stress

4. CONCLUSION

Three-dimensional textile composite was evaluated by using computer aided geometric modelling. Two different models having geometrical variation in 3D weave type was developed. Two types of textile composites (Angle interlock and Layer to layer) were model, and warp, weft and binder adjustments. Geometrical models were imported to finite element solver to perform multi set linear static test under compressive load. Results showed that overall volume fractions have significant influence on mechanical properties of the textile composites, especially influenced by the 3D arrangement of reinforcements.

ACKNOWLEDGEMENT

This work was supported by SELECTA project (No. 642642) H2020-MSCA-ITN-2014.

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