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Unit cell model of woven fabric textile composite for multiscale analysis

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Abstract

This paper presents a micromechanical unit cell model of 5-Harness satin weave fabric textile composite for the estimation of in-plane elastic properties. Finite element modeling of unit cell at mesoscopic level has been recommended over employing costly experimental setup for such sophisticated materials. The unit cell is identified based upon its ability to enclose the characteristic periodic repeat pattern in the fabric weave. Modeling of unit cell and its analysis for this new model are developed using an open source software, TexGen and a commercially available finite element software ABAQUS®. The scope of altering weave pattern and yarn characteristics is facilitated in this developed model. Several parametric studies were carried out in order to ascertain the effectiveness of the model and to investigate the effects of various geometric parameters such as yarn spacing, yarn width, fabric thickness and fibre volume fraction on the mechanical behavior of woven composites. Present analysis reveals that the values of Young's and shear modulus increased with increasing in the fabric parameters such as yarn width and fabric thickness. On the other hand it is decreased when the spacing between the yarns increased. A good comparision was obtained between the predicted results and available experimental and theoretical data in open literature for the developed unit-cell model and its suitability is tested for multi-scale analysis. The potential advantage of the present scheme lies in its ability which permits the textile modeling from building of textile fabric model to its solution including mesh generation undertaken using an integrated scripting approach thus requiring far less human time than traditional finite element models.

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Keywords: Unit cell; 5-Harness satin weave; finite element; in-plane; multi-scale

Nomenclature

v_f	volume fraction (%)
E	young's modulus (GPa)
G	shear modulus (GPa)
Greek symbols	
ν	poisson's ratio

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Subscripts	
11	longitudinal direction
22	transverse direction
33	transverse direction

1. Introduction

Textile composites are the promising new class of composites finding their applications in aerospace, automotive and manufacturing industries as they posses exceptionally high ratios of strain to failure in tension, compression or impact load as compared to traditional unidirectional prepreg composites [1]. Woven fabric are produced by weaving continuous fiber also called reinforcement by multiple weaving pattern viz. plain, twill, satin, basket etc., and then impregnating the weave with a base material called matrix to form the composite. Satin weave fabrics possess enhanced bidirectional properties within their plane, which gives rise to a higher specific strength and stiffness and improved dimensional stability as compared with conventional uni-directional composites [1]. The mechanical properties of such composites depends upon various factors such as fibre bundles, yarn spacing, yarn stacking sequence, yarn size, fiber orientation, fiber architecture and fiber volume fraction [2] which makes the modelling aspect of these composites extremely challenging. In the past many assumptions were made by several researchers [3][4] and numerous techniques [5][6][7] were adapted in order to anticipate the mechanical behavior of these complicated woven composites but however they lack in terms of computational efficiency, accuracy and level of validation. The effective properties of woven fabric textile composites can be easily determined by indentifying a periodic unit cell. The unit cell or a representative volume element (RVE) which is interconnected at discrete number of nodal points can be considered as the smallest possible building block for the textile composite, such that the composite can be created by assembling the unit cell in all three dimensions. The macro mechanical properties of the woven fabric composites are evaluated with the help of periodic unit cell structure by using micromechanical methods. Current research work is intended to estimate the mechanical properties of 5-Harness satin weave composite unit cell with minimum modelling and computational effort. Towards this end the geometric modeling of the unit cell is done using open source codes TexGen [8] developed at University of Nottingham (U.K.) while the analytical aspects are performed with help of FEM based simulation software ABAQUS®. The proposed modeling route is found to be fully automated and most reliable.

2. Unit Cell Geometry

The unit cell which is an essential component of textile modeling is modeled using TexGen with the assumption that both the warp and weft yarns posses similar geometric and material properties. The cross-section of yarns confined in the unit cell are assumed as elliptical in the present study. The schematic for 5-Harness satin weave unit cell generated by TexGen is shown in Fig.1. The dimensions (length (l) x width (w) x depth (t)) of the unit cell and the set of input data used in geometric modeling are depicted in Table.1 and 2.

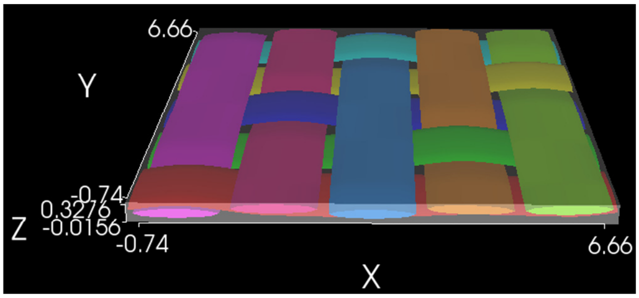


Fig.1. Geometric model for 5-Harness satin weave fabric

Table 1. Unit cell size (mm)

Length	Width	Thickness	Volume
7.4	7.4	0.34	18.79

Table.2. Input data for yarn modeling (mm)

Yarn Spacing	Yarn width	Fabric thickness	Number of Warp Yarns	Number of Weft Yarns
1.48	1.32	0.312	05	05

3. Finite Element Modeling

The geometric model of unit cell which is created using TexGen is further transferred to ABAQUS® through python script for FE analysis. For this purpose TexGen and ABAQUS® are used in combination because of their similarity in Python scripting interfaces as the codes required for linking the above two were written by the researchers of University of Nottingham enabling the reproduction of textile models within a modelling environment automatically. The geometric model generated by the TexGen is first saved in the form of .tg3 file with complete textile and meshing data, then after it can be exported into any of the suitable options depending upon the nature of problem as ABAQUS Voxel File environment in the present case. Issues related to FE modelling such as contact between the yarns, creation, submission and detailed analysis of the job are taken care of by the fully automated python script which contains the code that creates the TexGen model while the outer surfaces of the yarns are defined when the program loops over the hierarchy of textile. Three dimension 8 noded brick element with reduced integration (C3D8R) were found to be the most applicable element for these analyses as brick elements have the ability to incorporate midside nodes (producing 21-node elements) and several material models. Eight-node element means, every element consists of 8 nodes while reduced integration means that the order of integration is lower than that of full integration. The order of integration refers to single point in each element which is placed at the centroid. The total number of elements and the nodes involved in the analysis are 50000 and 54627 respectively. However, the model was found insensitive to further refinement of mesh. In the present study the unit cell is subjected to periodic boundary condition as by the application of such boundary conditions the model is equivalent to an infinitely large fabric undergoing uniform deformation. This also helps to simulate the behavior of large fabric which is many times the size of a single unit cell. Uniaxial loads are applied to the unit cell at any point in the cell termed as constraint driven point assigned as x=0, y =1, z =2, xy = 3, xz = 4 and yz = 5 in the analysis to obtain the elastic properties [9]. Macroscopic strain treated as independent degree of freedom to the system can be prescribed as load. The schematic of the FE model for the 5-Harness satin weave unit cell with and without matrix is shown in Fig.2.

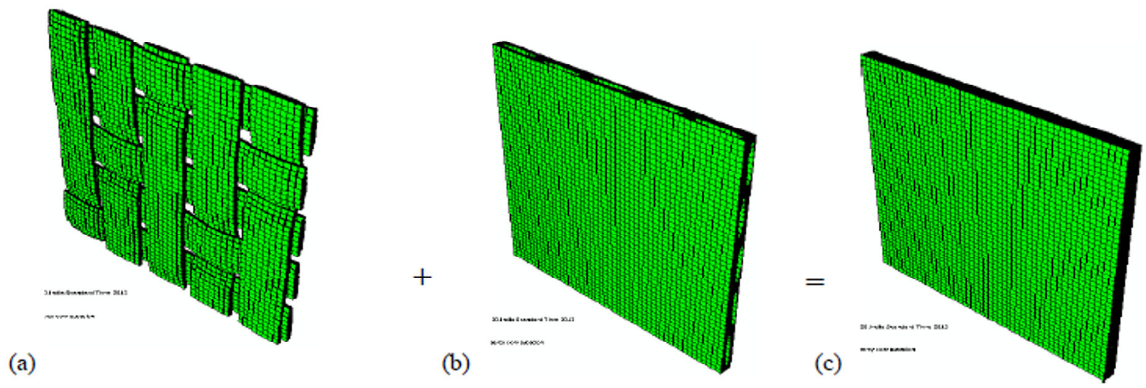


Fig.2. Finite element model showing (a) Yarns (b) Matrix pocket (c) Composite

4. Material Definition

The yarns in the present analysis are considered as an orthotropic solid bodies, whose longitudinal direction which is parallel to fiber is defined by 11 and transverse plane is designated by the directions 22 and 33 respectively, while the PolyPhenylene Sulfide (PPS) matrix in the modeling scheme is assumed to be isotropic. Mechanical behavior of unit cell is predicted by incorporating a transversely isotropic material law. The material property of 5-Harness satin weave fabric consisting of T300JB carbon fibres/PPS matrix composite [10] is mentioned in Table 3 and 4 respectively. The orthotropic behaviour of the yarns can be defined by a 3D stiffness matrix consisting of nine independent constants as shown in Eq.1. Incorporating transversely isotropic yarn behaviour the material law results in the following set of equation $E_{22} = E_{33}$, $\upsilon_{12} = \upsilon_{13}$, $G_{12} = G_{13}$ and Eq.2.The final matrix consist of the five independent constants namely E_{11}, E_{33}, υ_{12}, υ_{23} and G_{12}.

Table 3. Material Parameters used in simulation (Moduli in GPa) [10]

E_{11}	E_{33}	υ_{12}	υ_{23}	G_{12}	G_{23}
231	28	0.26	0.3	24	10.7

Table. 4 Elastic properties of PPS matrix [10]

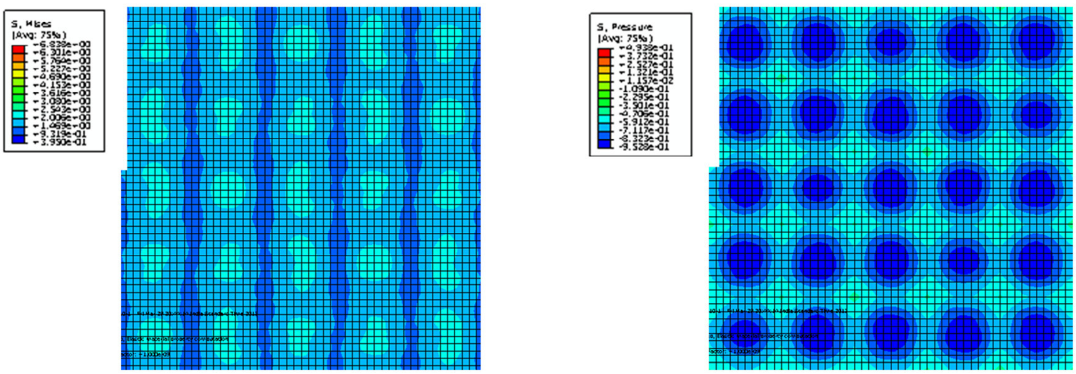
E(GPa)	υ
3.80	0.37

$$\begin{bmatrix}\varepsilon_{11}\\ \varepsilon_{22}\\ \varepsilon_{33}\\ \varepsilon_{23}\\ \varepsilon_{13}\\ \varepsilon_{12}\end{bmatrix} = \begin{bmatrix} \frac{1}{E_{11}} & -\frac{\upsilon_{12}}{E_{11}} & -\frac{\upsilon_{13}}{E_{11}} & 0 & 0 & 0 \\ -\frac{\upsilon_{12}}{E_{11}} & \frac{1}{E_{22}} & -\frac{\upsilon_{23}}{E_{22}} & 0 & 0 & 0 \\ -\frac{\upsilon_{13}}{E_{11}} & -\frac{\upsilon_{23}}{E_{22}} & \frac{1}{E_{33}} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{23}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{13}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{12}} \end{bmatrix} \times \begin{bmatrix}\sigma_{11}\\ \sigma_{22}\\ \sigma_{33}\\ \sigma_{23}\\ \sigma_{13}\\ \sigma_{12}\end{bmatrix} \quad (1)$$

$$G_{23} = \frac{E_{33}}{1+\upsilon_{23}} \quad (2)$$

5. Results and Discussions:

In this section the FE model developed in the previous section is used to evaluate the elastic properties of 5-Harness satin weave woven fabric composites. Further the properties predicted are compared with those obtained by experimental means and Daggumati et.al [10]. Uniaxial elastic load cases which were applied at any point in the unit cell were analyzed to obtain the three normal Young's moduli and the Poisson's ratios of the composite reinforced with the glass carbon fiber. The macroscopic strain $\varepsilon_x^0, \varepsilon_y^0, \varepsilon_z^0, \gamma_{yz}^0, \gamma_{xz}^0$ and γ_{xy}^0 be treated as six extra degrees of freedom through which loads to the unit cell can be prescribed and to these extra degrees of freedom macroscopic stresses to the UC can be applied as concentrated force. The stress distribution on a composite unit cell is shown in Fig.3.



(a) (b)

Fig.3.Stress distribution over the fabric unit cell (a) S. Mises (b) S. Pressure

Table 5. Predicted values of elastic properties of 5-harness satin weave woven composite

	Experiment [10]	Theoretical [10]	Present FEA
E_{11}	57	56.49	57.5
E_{22}	57	56.49	57.5
G_{12}	4.17	4.28	6.03
G_{23}	NA	3.48	2.79
υ_{12}	0.05	0.08	0.08
υ_{23}	NA	0.41	0.42

Experimental and Theoretical elastic properties of the 5-harness satin weave woven composite are shown and compared with present analysis in Table 5. There are 6 load cases (acting in 1 direction) each of them are applied separately to the constraint driver nodes 0, 1,2,3,4,5 and the output will give the modulli (E_x, E_y, E_z, G_{xy}, G_{xz} and G_{yz}) corresponding to each load case. The output is obtained in .rpt file in the form of displacement (6 outputs for each constraint driven nodes i.e. total of 36) which correspond to the strain's and therefore giving a unit stress, the Young's modulus is simply 1/strain and hence we can calculate all the modulli for each constraint driven nodes. The reasonable predictions of in-plane elastic properties are obtained from the present modeling technique. The in-plain Young's Moduli and Poisson's obtained from present FEA are found to be in good agreement with those obtained from Daggumati [10] and experimental results [10]. The reason behind the difference in results is that the FEA gives an upper bound solution as it runs under iso-strain condition while theoretical models gives a lower bound solution because it runs under iso-stress condition.

6. Parametric Study

A parametric study has been carried out with the aim to explore the effectiveness of the model and to evaluate the influence of geometric and material parameters on the overall mechanical behaviour of woven composite. Independent parameters such as yarn spacing, yarn width, fabric thickness and fibre volume fraction were varied and the effects of variation on various moduli and poisons ratio were examined thoroughly.

6.1 Effect of yarn spacing

The yarn spacing which can be termed as the distance from the edge of one yarn to the corresponding edge of an adjacent yarn. Increasing the spacing between two consecutive yarns while keeping the yarn width and fabric thickness as constant results in reduction of the yarn crimp angle and overall fibre volume fraction. The effect of yarn spacing on Young's modulus (E_{11} & E_{33}) and Poisson's ratio has been shown in Fig.4(a) and (b).

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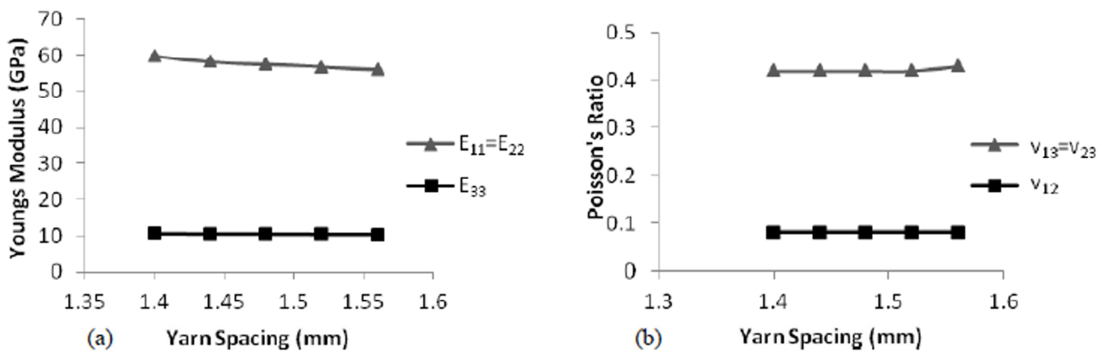

Fig.4 (a) Effect of yarn spacing on $E_{11}=E_{22}$ & E_{33} (b) Effect of yarn spacing on ν_{12}& $\nu_{13}=\nu_{23}$

6.2 Effect of yarn width

The effect of the increase of yarn width on longitudinal and transverse modulus at constant yarn spacing and fabric thickness has been shown in Fig. 5(a) and (b) respectively. It is observed from the figures that as the fibre volume fraction increases due to increase in yarn width the value of longitudinal and transverse modulus also increase gradually while the value of poison's ratio almost remains constant.

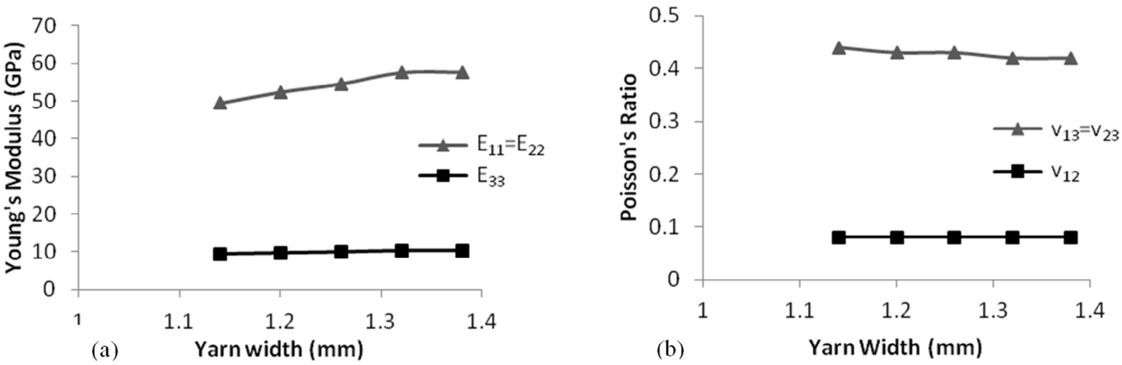

Fig.5 (a) Effect of yarn width on $E_{11}=E_{22}$ & E_{33} (b) Effect of yarn width on ν_{12} & $\nu_{13}=\nu_{23}$

6.3 Effect of fabric thickness

The behavior of Young's and shear modulus with increasing fabric thickness and constant width as well as spacing of the yarns has been shown in Fig.6 (a) and (b). The longitudinal modulus in both the cases was found to increase due to dramatic change of the yarn crimp angle and little change in fibre volume fraction. The yarn crimp angle increases with increase in fiber volume fraction thereby increasing the off-axis angle of the yarn. However the transverse modulus in both the cases doesn't get affected a lot as compared to longitudinal modulus.

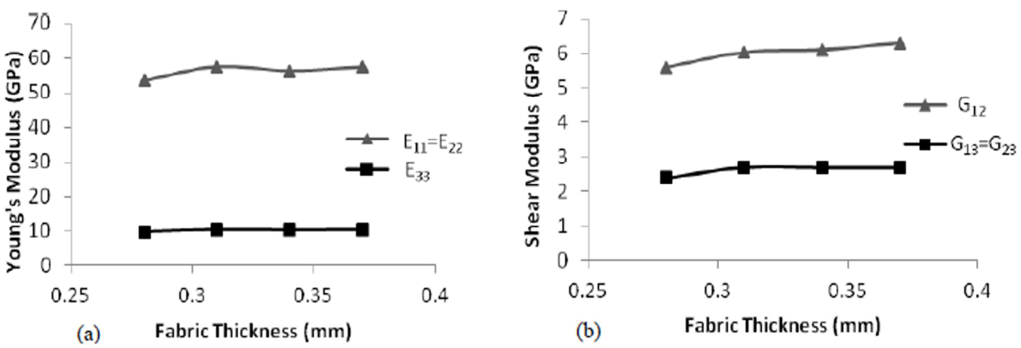

Fig.6 (a) Effect of fabric thickness on $E_{11}=E_{22}$ & E_{33} (b) Effect of fabric thickness on G_{12} & $G_{13}=G_{23}$

7. Conclusion

This paper presents a fully automated scheme for mechanical modeling of textile reinforced composites. The foremost advantage of the present scheme lies in its ability by which it permits the textile modeling from building of textile fabric model to its solution including mesh generation, using an integrated scripting approach. Unit cell analysis of 5-Harness satin weave fabric composite is performed and the results are compared and found to be in reasonably good agreement with the experimental data and theoretical model for the similar material available in the open literature. The reason behind higher predicted values of shear modulus of the composite could be attributed to the possible warpage of woven fabrics during its fabrication process. Exhaustive parametric study reveals the dependency of various material and geometrical parameters on the modulus and strength of woven composite. A transversely isotropic material law with non-linear transverse mechanical properties is adapted by the ABAQUS® FE software in the present analysis. The foremost advantage associated with the present model is its ability to clearly identify and process the FE analysis in those areas where fibre volume fraction is not constant. The developed model also facilitates the scope for altering the weave pattern and yarn parameters such as yarn spacing, yarns width, fabric thickness and different material properties for the warp and fill yarns.

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