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Geometric modeling and finite element analysis of kevlar monolithic and carbon-kevlar hybrid woven fabric unit cell

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ABSTRACT

The prediction of the mechanical strength of composites must be known before use or fabrication. The computerized modeling and analysis helps in prediction of the realistic performance of the composite products. The current research work presents the modeling routs of yarns, yarn interpolation for path, cross-section, and orientations with finite element analysis of woven fabric reinforcements. The geometrical modeling routes of textile woven reinforcements at meso-scale described by using TexGen 3.10, which is a python scripted software package, developed by the polymer composites group at the University of Nottingham, UK, works as a preprocessor for characterization of textile reinforcements. The finite element analysis of textile woven reinforcements is done by using a commercially available software package ABAQUS 6.14-5. Due to the similarity of python scripted codes in both the software's, ABAQUS is considered as an analysis tool for textile reinforcements among the so many FE based platforms. Textile woven fabric unit cell having plain and twill weaving patterns are explained with Kevlar (monolithic) and Carbon-Kevlar (hybrid) yarns with finite element compression behaviour analysis, and discussed to understand the mechanical performance of polymer textile composites.

Selection and of the scientific committee of the 10th International Conference of Materials Processing and Characterization.

1. Introduction

Composites are used worldwide due to their extreme advantages over the individual material as high strength/stiffness to weight ratio, corrosion resistance, high durability, high flexural modulus to carry demanding loads, high impact strength, chemical resistance, toughness and design flexibility etc. High strength advanced polymer textile composites having their advantages in various areas like automobile, military, space aircraft, etc. [1]. Composites are made by two different phase materials, namely reinforcement and matrix, which are not soluble to each other. Reinforcement plays a vital role in the mechanical and structural performance of composites, as it carries and uniformly distributes the whole load, applied on the matrix. The strength of the reinforcement is much greater than strength of matrix but the strength of matrix affects many mechanical properties. The cross-section, orientation, material, tow size, fiber type of the reinforcement material plays a significant role in the mechanical performance of composites.

The fiber may be synthetic (carbon, kevlar, glass etc.) or natural fiber (flax, hemp, jute, kenaf, sisal etc.) and matrix may be thermoplastic (polyamide, polypropylene, neoprene, teflon, bakelite, acrylic, acrylonitrile butadiene styrene, nylon, polybenzimidazole, polycarbonate, polystyrene, polyvinyl chloride etc.) or thermosetting matrix (epoxy, polyester, vinylesters, polyimide, phenolic resins, amino resins etc.).

There are so many methods available for the manufacturing of polymer matrix composites such as hand lay-up, spray lay-up, RTM, VARTM, compression, injection molding, pultrusion, autoclave, filament winding, etc. The textile composite manufacturing hierarchy (Fig. 1) defines the stages of modeling of a composite product from fiber. The virtual modeling and analysis using some software tool approach are helpful in the prediction of realistic performance of a composite product. The prediction of realistic performance of textile and textile composite products depends on the accuracy of modeling and post-processing analysis approach used. In the presented research work the geometrical modeling of textile woven reinforcement is done by using commercially available

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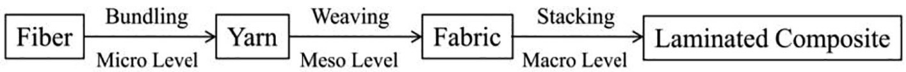

Fig. 1. Composite manufacturing hierarchy.

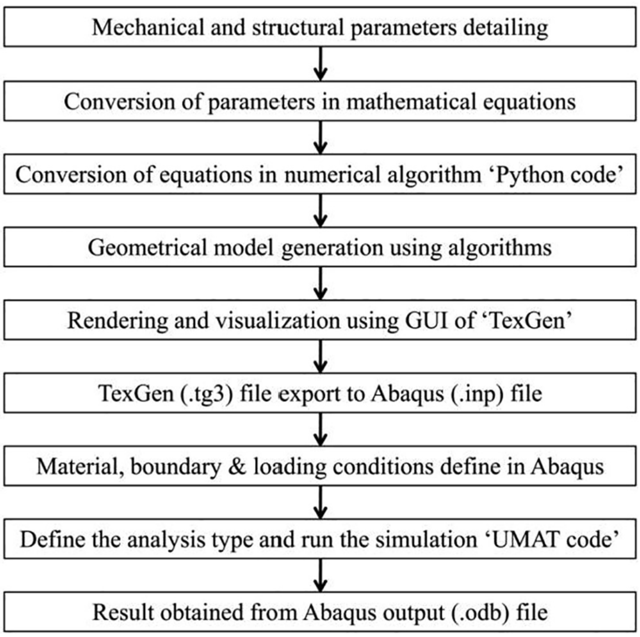

Fig. 2. Hierarchy of textile composite modeling and FE analysis.

Fig. 3. Yarn (10 mm) having 5 nodes, yarn centre line (left), yarn render model (right).

python scripted software platform 'TexGen 3.10' and finite element (FE) analysis is done by using 'ABAQUS 6.14-5'.

TexGen – a python scripted commercially available software platform, used for the geometrical modeling of yarns and different types of textile woven reinforcements with the matrix and reinforcement property assignment involving so many modeling routes, developed by the Polymer Composites Group at the University of Nottingham, UK. It is a pre-processor textile weave modeling tool that uses the python coding. ABAQUS is a post-processing tool, used for the FE analysis of composite product involving geometry import, coordinates definition, material assignment, boundary, loading conditions, results and graphs etc. The hierarchy of textile composites analysis (Fig. 2) is defined here from geometric modeling to finite element post-processing results [2].

The existing literature is the compression behavior study of woven plain and hybrid composites. The reinforcements are Carbon yarn and Kevlar yarn woven in plain and twill weaving patterns with yarn level hybridization. This textile is weaved with plain and twill pattern having warp yarn of Carbon and weft yarn of Kevlar. The 2×2 twill weaving pattern offers good dimensional stability in both the directions results in higher out of plane strength [10]. The reinforcement is impregnated with resin matrix at pre-determined controlled level. The matrix is used to bind the reinforcement, protect them from handling and environmental damage etc. The matrix used in the study is thermoset matrix epoxy. The presented research work is intended to elucidate the modeling routes of woven fabric textile composite using TexGen and its FE analysis using computational approach.

2. Geometric modeling of yarn

The realistic geometrical modeling is necessary to predict the actual performance of a textile composite product. Woven fabric textile composites can be defined as the building blocks of fibers

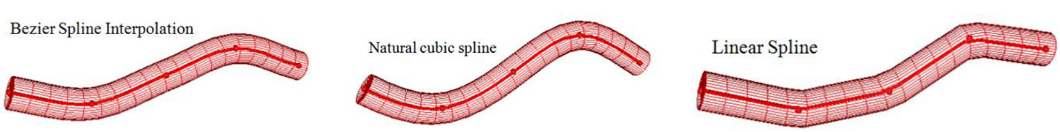

Fig. 4. Yarn path interpolation between nodes.

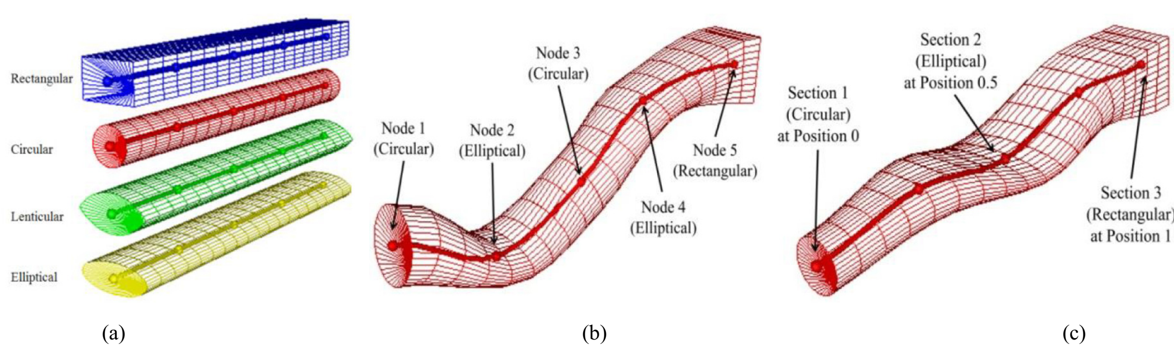

Fig. 5. Cross-section interpolation (a) yarn cross-sections, (b) between nodes, (c) between positions.

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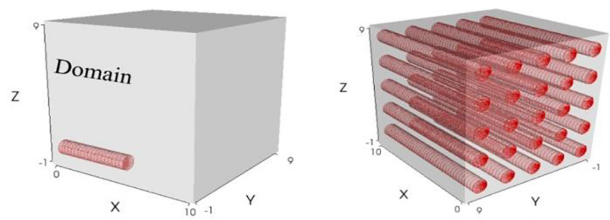

Fig. 6. Repetition of yarns in a volumetric domain to create fabric.

and yarns. Yarn/tow is the bundle of finite number of fibers in parallel or twisted formation; similarly the woven fabric is weave building blocks of yarns and the composite laminate is the stacked block of weaves impregnated with controlled level of resin matrix. The modeling of yarns plays a vital role in weave performance. So many parameters are involved in the yarn modeling i.e. yarn path, orientation, interpolation, positioning, cross-section etc.

The path of yarn can be specified by using centerline and it is the series of nodes (Fig. 3 shows a linear yarn of 10 mm length having 5 nodes). Yarn path is the position interpolation of curves at

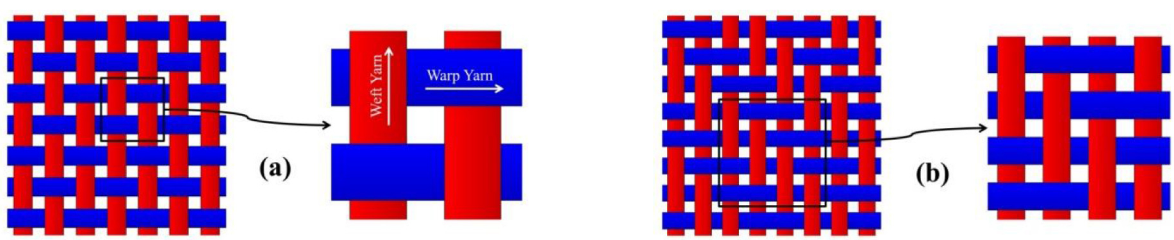

Fig. 7. Unit cell model for, (a) plain woven fabric (b) twill woven fabric.

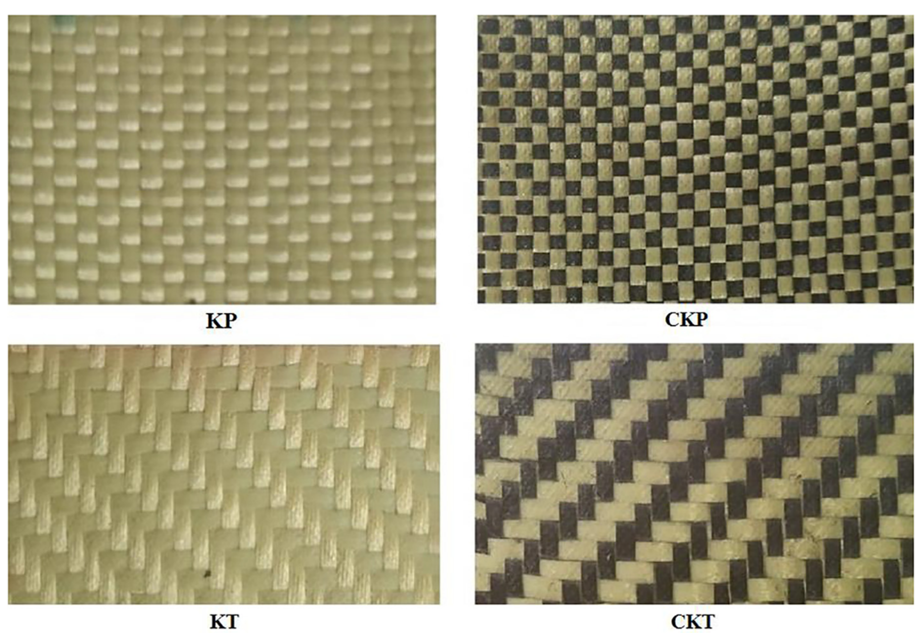

Fig. 8. Monolithic kevlar & hybrid carbon-kevlar woven fabric in plain and twill weaving patterns.

Table 1
Input date for unit cell modeling (mm).

Weaving pattern	Yarn width	Yarn spacing	Fabric thickness	Warp yarns	Weft yarns
Plain	0.8	1	0.2	2	2
Twill	0.8	1	0.2	4	4

Table 2
Unit cell dimensions (mm).

Weaving pattern	Length (l)	Width (w)	Thickness (t)	Volume (v)
Plain	2	2	0.22	0.88
Twill	4	4	0.22	3.52

various nodes (Fig. 4) i.e. linear, natural and bezier spline interpolations [9]. The cross-section of yarn (Fig. 5) can be defined as a two dimensional shape in which all the fibers are involved and obtained by cutting the yarn from a plane perpendicular to the path of yarn. It may be elliptical, rectangular, circular, lenticular in shape [3,4]. The cross-section interpolation between nodes and positions in yarn are also presented in this section. The modeling tool TexGen also facilitate to repeat yarns (Fig. 6) in all three directions in a defined domain to create the realistic effect of boundary and loading conditions.

The domain in TexGen is defined as a considerable space to model the textile reinforcements. The yarns have some mechanical properties that are required to be defined in modeling tool TexGen such as yarn linear density, fiber density, fiber area, fiber diameter, fibers per yarn, young's modulus, shear modulus, poisson's ratio etc. Also the fiber volume fraction can be directly calculated by using the python scripted software platform TexGen.

3. Unit cell geometrical model of woven fabric

The composite laminated structure consists of finite number of building blocks of repetitive elements of same volume and material. This repetiting yarn volumetric elements of identical weaving pattern is defined as representative volume element (RVE) or unit cell. The unit cell is the smallest unit of a textile composite. It is very complicated to model and analyze the whole laminated composite structure due to a large number of elements and modeling complexities. TexGen facilitates here to assign repeats of unit cells to get the desirable realistic effect of loading conditions on textile composites [5].

The unit cell model of plain and 2 × 2 twill weave (Fig. 7) is considered here in the current study. The cross-section of yarns taken for consideration is elliptical in shape. The extensive literature review on weave modeling was found from Sherburn [7]. The plain and twill textile woven fabric consist of two same or different material yarns, namely warp yarn (major axis) and weft yarn (minor axis). The comparative study in the current literature is done on four different woven fabrics (Fig. 8), namely plain woven kevlar (warp) – kevlar (weft), plain woven carbon (warp) – kevlar (weft), 2 × 2 twill woven kevlar (warp) – kevlar (weft), and 2 × 2 twill woven carbon (warp) – kevlar (weft) and the notation for these fabrics are given as KP, CKP, KT, CKT respectively.

The geometrical input data required for modeling the textile woven fabric are yarn width, yarn spacing, fabric thickness, number of warp & weft yarns are depicted in Table 1 and the length (l), width (w), thickness (t), & volume (v) of unit cell are depicted in Table 2 [5].

4. Finite element modeling

4.1. Python scripting interface

The unit cells of plain and 2 × 2 twill weave fabrics were modeled on python scripted software platform TexGen. The

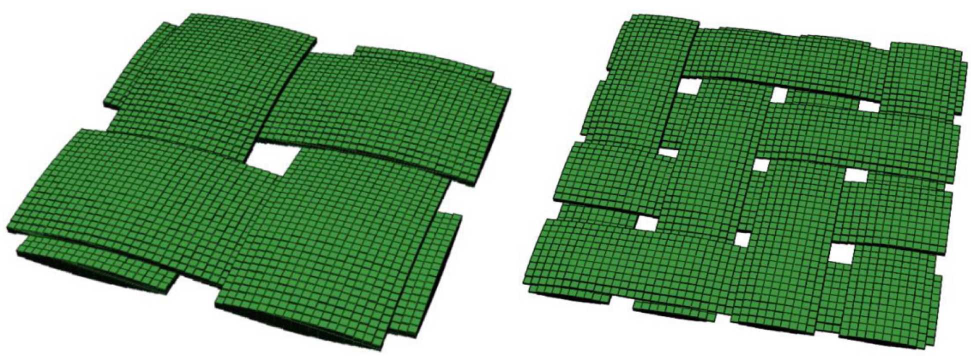

Fig. 9. Textile dry fiber file of plain weave (left) and twill weave (right) unit cell.

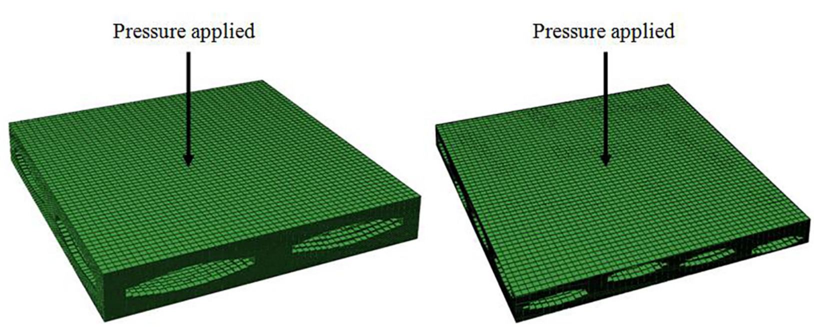

Fig. 10. Compression (uniform pressure distribution) setup of plain weave (left) and twill weave (right) unit cell composite structure.

Table 3
Material properties.

Material	Density (tonne/mm^3)	E_{11} (MPa)	E_{22} (MPa)	E_{33} (MPa)	ν_{12}	ν_{13}	ν_{23}	G_{12} (MPa)	G_{13} (MPa)	G_{23} (MPa)
Carbon	1.76e−9	220,690	13,790	13,790	0.20	0.20	0.25	8970	8970	4830
Kevlar	1.467e−9	151,700	4140	4140	0.35	0.35	0.38	2900	2900	1800
Epoxy	1.25e−12	E = 3500			ν = 0.35					

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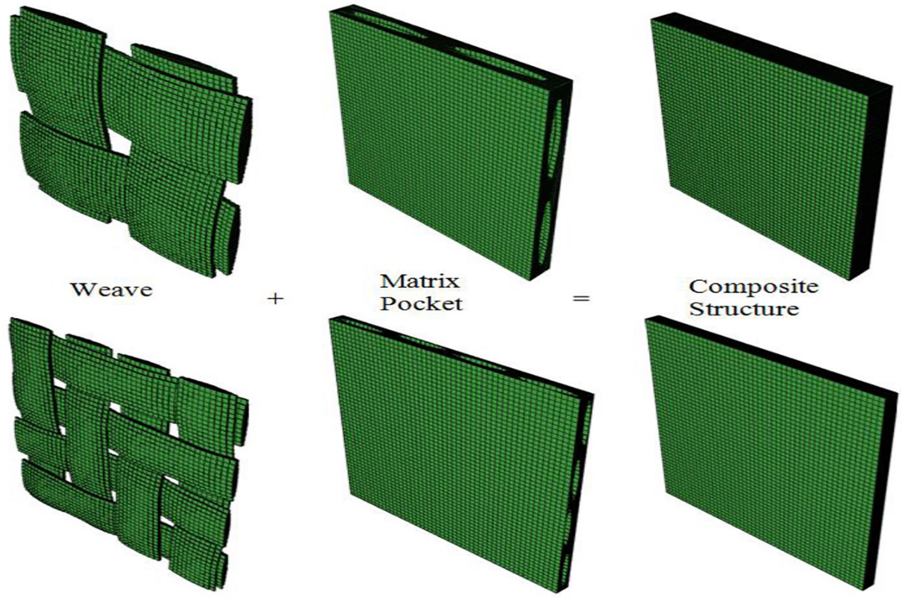

Fig. 11. Mesh view of plain and twill woven fabric unit cell with matrix structure.

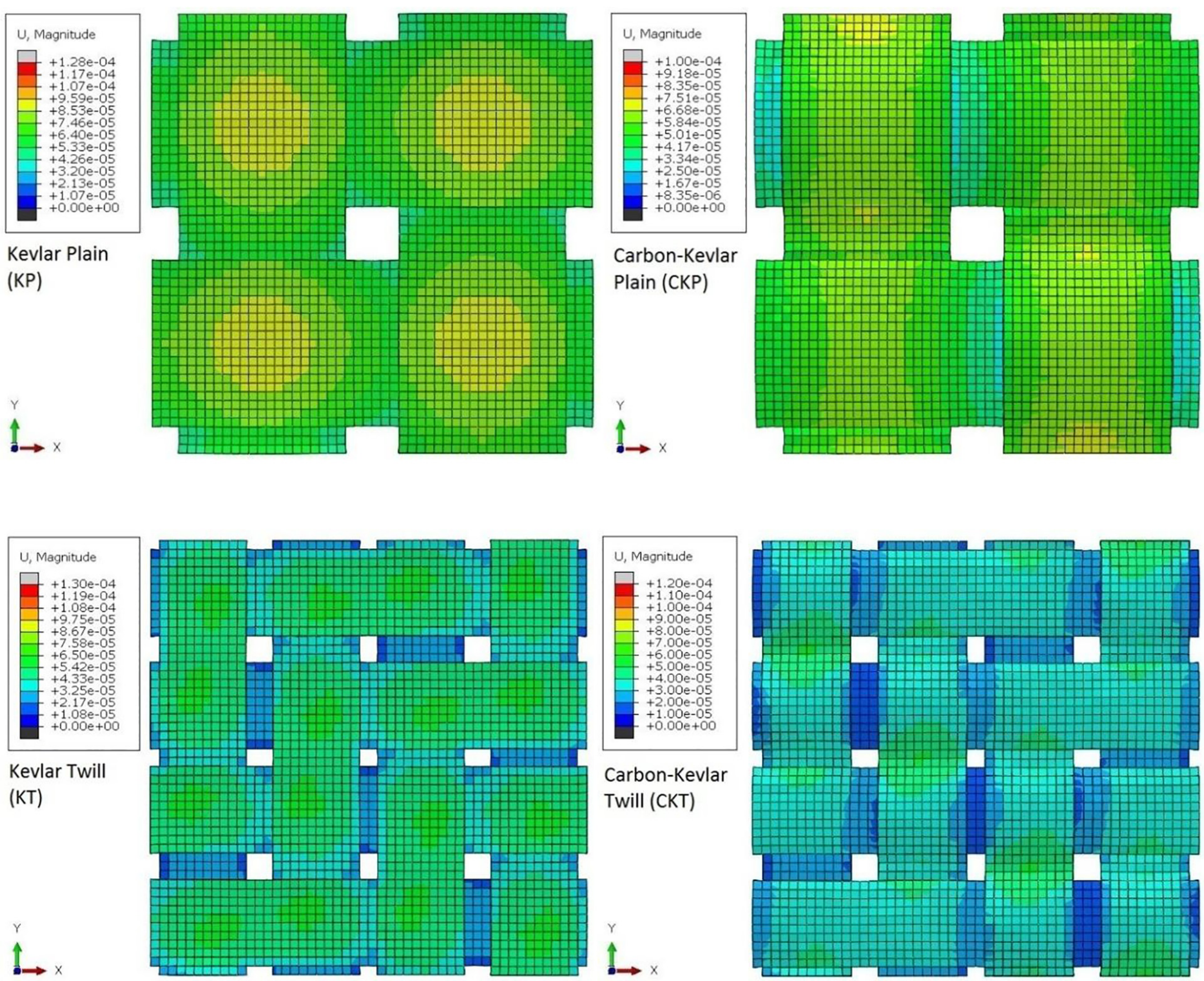

Fig. 12. Displacement (m) distribution contour plot of KP, CKP, KT and CKT woven fabric.

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geometrical model of textile weave is required to be analyzed by using some finite element based software package, which should be commercially available and having python scripted interface to get the prediction of realistic results. Among the so many software's which are commercially available, the FE based software platform 'ABAQUS' has the integrated approach of similarity in python scripted coding and take care of the textile weave modeling data such as contact of yarns, mechanical properties, meshing data exported from the modeling platform 'TexGen' [5,8].

The geometrical model of textile weave created by using TexGen can be exported in many extension file formats i.e. .tg3, .inp, .iges, .step etc. The reinforcement with matrix, voxel file (.inp) exported from TexGen, can be imported on ABAQUS for further FE analysis. The integrated similar coding interface in both the platforms facilitates to analyze the textile composite for realistic results [6]. The weave files with matrix pocket (Figs. 9 and 10) were used for compression behaviour analysis in ABAQUS to get the effect of applied load on woven fabrics.

4.2. Material properties

The textile composite consists of two phases, reinforcement and matrix, considered for compression behaviour analysis. The matrix material considered here is epoxy and the reinforcement materials are woven Kevlar monolithic and Carbon-Kevlar hybrid fabrics. The textile weave unit cell considered here are the solid orthotropic volumetric elements. The orthotropic material behavior can be defined by nine independent engineering constants presented in the stiffness matrix (Eq. (1)).

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

Here, E, ε, σ, ν, G represents Young's moduli, microscopic strain, microscopic stress, Poisson's ratio, and Shear moduli respectively. Due to the transversely isotropic behavior of the yarn material, Eq. (2) can be considered.

$$E_{22} = E_{33},\ G_{12} = G_{13},\ \nu_{12} = \nu_{13} \quad (2)$$

The material properties of Carbon, Kevlar and Epoxy are shown in Table 3. The subscript 11 is used for longitudinal direction and 22, 33 used for transverse directions. The material properties (Table 3) are defined in ABAQUS for individual parts during FE analysis [5,6].

4.3. Meshing

The voxel file (.inp) of composite structure converted into the finite number of elements and nodes using ABAQUS meshing tool for the micro-level elementary analysis. The hexahedral elements are considered for analysis. The eight-noded three-dimensional brick elements with reduced integration C3D8R are selected for meshing of the woven fabric unit cell and matrix (Fig. 11). The total number of nodes and elements are 132,657 and 125,000 respectively.

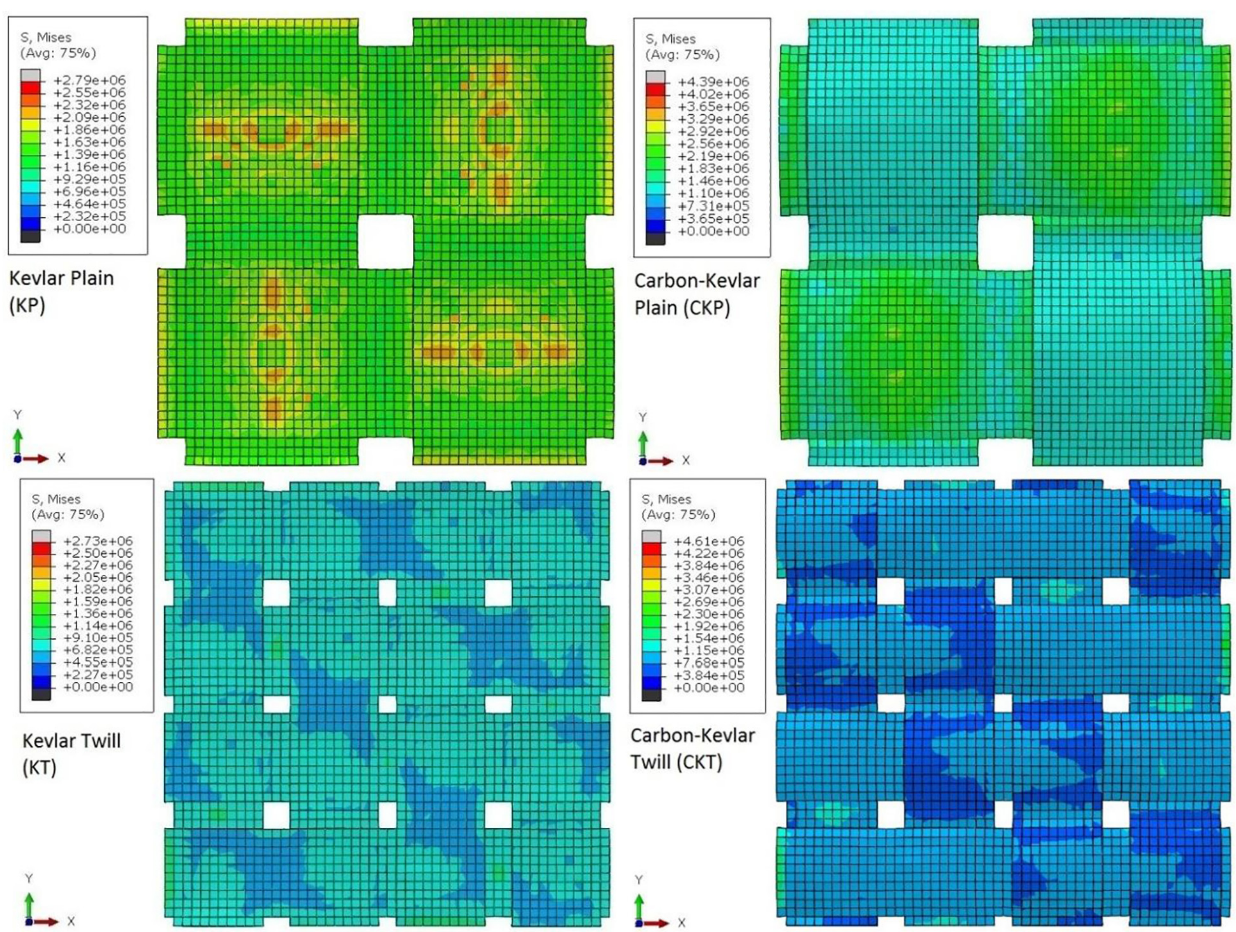

Fig. 13. Stress (Pa) distribution contour plot of KP, CKP, KT and CKT woven fabric.

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4.4. Boundary conditions

The master-slave surface approach is used in the current analysis to create the desired boundary conditions and loading. Fixed support is applied to the bottom surface of the matrix structure using Encastre tool (displacement and rotation in all directions are zero) and top surface is constrained to move only in vertical direction (perpendicular to weave axis). The compression pressure of 4 MPa is applied on the top surface of the matrix. The effect of applied load on Carbon and Kevlar yarns in terms of displacement, stress and strain energy can be analyzed using FEA tool.

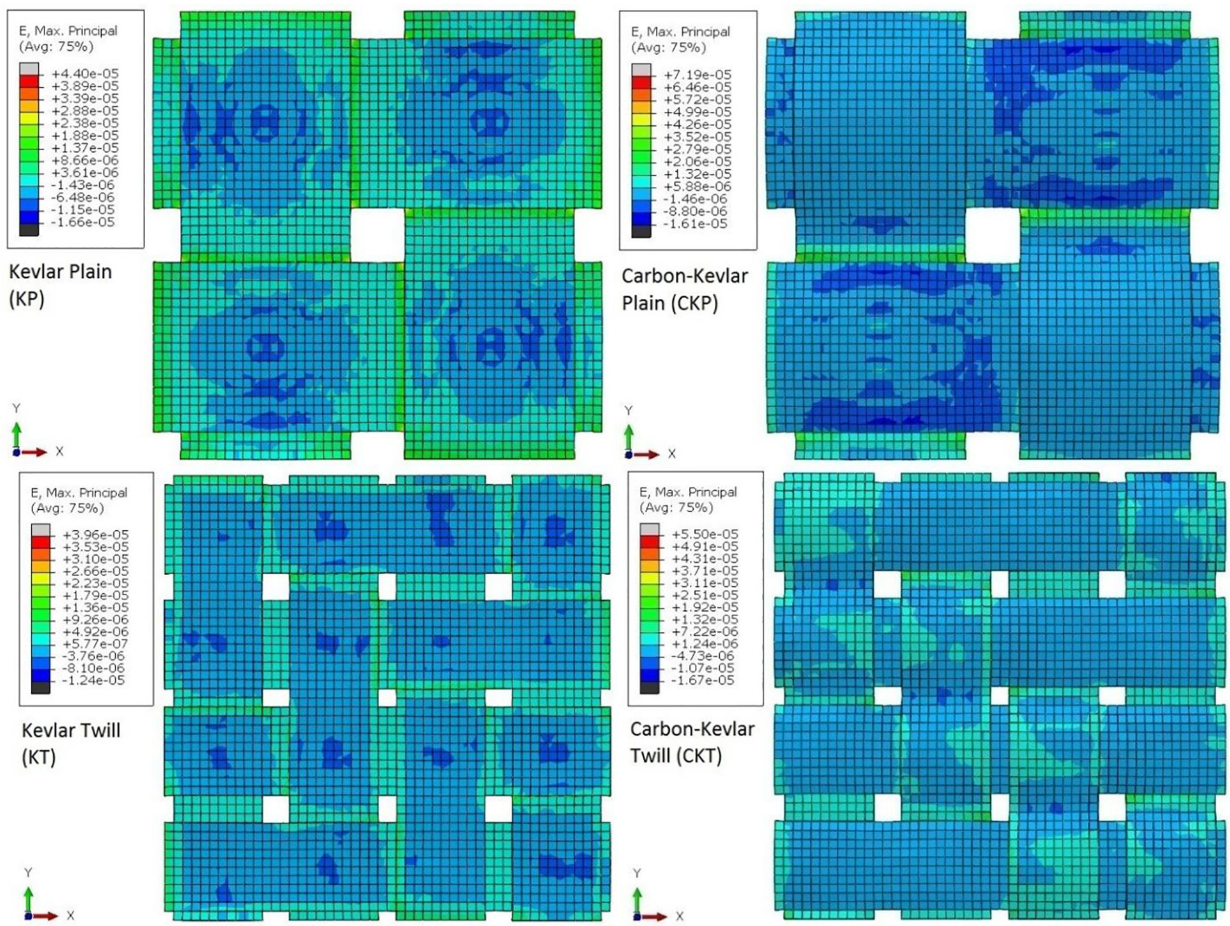

Fig. 14. Strain energy (J) distribution contour plot of KP, CKP, KT and CKT woven fabric.

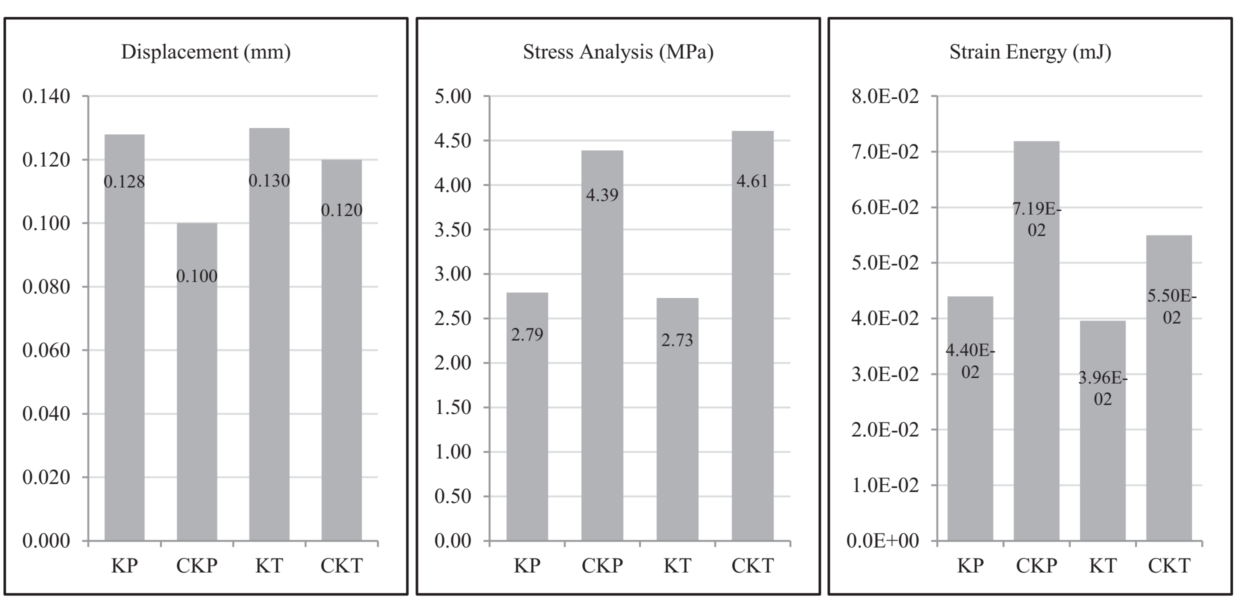

Fig. 15. Result analysis of KP, CKP, KT and CKT woven fabric in terms of displacement, stress and strain energy.

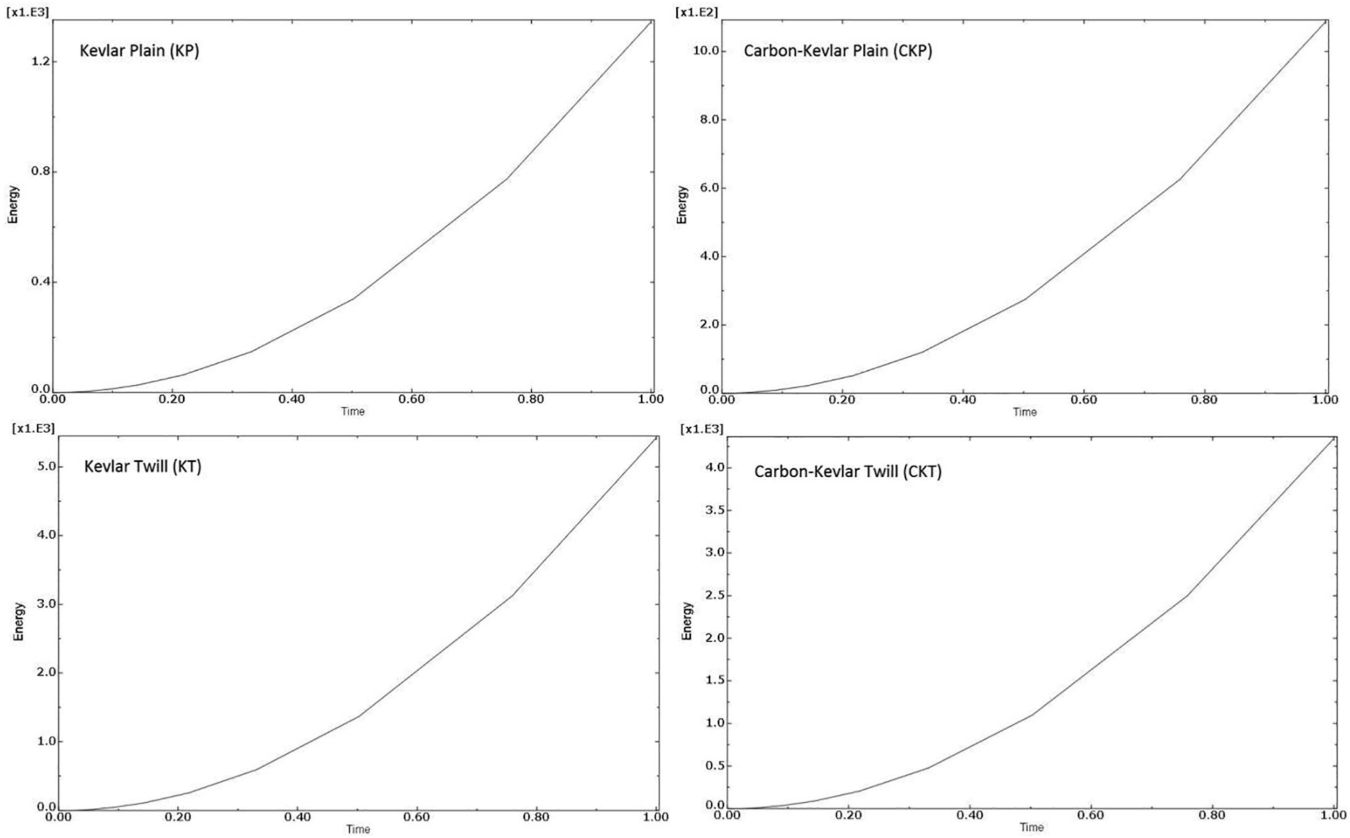

Fig. 16. Strain energy plot of KP, CKP, KT and CKT woven fabric.

4.5. Finite element analysis and results

The preprocessing of the woven fabric unit cell of plain monolithic kevlar, plain hybrid carbon-kevlar, twill monolithic kevlar and twill hybrid carbon-kevlar is done by using modeling tool TexGen. After preprocessing, finite element model is created by using FE software package ABAQUS, which involves import of model, material assignment, meshing and assigning boundary conditions. The prepared unit cell model is further required to analyze for stress, displacement and strain energy. The model analyzed here represents the compression of composite structure and its effect on woven fabric unit cell in terms of stress, displacement and strain energy plots. The commercially available software platform ABAQUS facilitates to analyze the model for mechanical, thermal and fracture characterization for realistic results prediction.

The displacement analysis (Fig. 12) shows the smallest displacement occurred in Carbon-Kevlar hybrid plain woven fabric and the highest in Kevlar monolithic twill woven fabric. Stress analysis (Fig. 13) shows that the smallest stress generated in Kevlar monolithic twill woven fabric and highest in Carbon-Kevlar hybrid twill woven fabric. The strain energy analysis (Fig. 14) represents that the highest strain energy generated in Carbon-Kevlar hybrid plain woven fabric and it is minimum in Kevlar monolithic twill woven fabric. Result comparison of all the fabrics in terms of displacement, stress and strain energy presented in Fig. 15 and the strain energy plots are presented in Fig. 16. The analysis is significant in prediction of the mechanical performance of woven fabric composites.

5. Conclusion

The textile woven fabric unit cell represents the smallest unit of the woven fabric. The textile weave modeling methodology was described using the python scripted software package TexGen. Thus the utility of TexGen are also explained in the preprocessing of the textile woven reinforcements. The similar python coding interface in both preprocessor and postprocessor facilitates to analyze the textile weave unit cell model to get realistic results. The postprocessor ABAQUS having the capability to import the TexGen made weave file in (.inp) file format due to the integrated approach of python scripted interface. Finite element analysis in ABAQUS facilitates to characterize the unit cell model for mechanical and fracture analysis. The finite element analysis was done to get the displacement, stress and strain energy results. The Carbon-Kevlar hybrid plain woven fabric stored maximum amount of strain energy and the displacement occurred was smallest. Kevlar monolithic twill woven fabric stored smallest amount of strain energy with maximum displacement. Result analysis shows the best mechanical performance in Carbon-Kevlar hybrid plain woven fabric composites. It can be further use where the high performance is required in physical applications.

CRediT authorship contribution statement

Pawan Sharma: Conceptualization, Methodology, Writing - review & editing. **Pragati Priyanka:** Visualization, Investigation. **Harlal Singh Mali:** Supervision. **Anurag Dixit:** Software, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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