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Finite Element (FE) Shear Modeling of Woven Fabric Textile Composite

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Abstract

This paper demonstrates the modeling of woven fabric textile composite under in-plain shear loading. The geometric modeling of fabric unit cell is modeled using TexGen textile modeling schema developed at the University of Nottingham. The yarns in the present scheme are treated as solid volume whose modeling depends upon various parameters such as yarn path, yarn cross-section, yarn surface. Periodic boundary conditions were identified to simulate the realistic nature of repetitive fabric unit cell. Transversely isotropic material law with non-linear transverse mechanical properties is incorporated using finite element (FE) simulation software ABAQUS®. This approach is initially validated for pure in-plain shear and compression loading; later on it is used to simulate the behavior of fabric under the combination of these loads which practically occurs during forming process. A successful prediction of shear force versus shear angle are made and was found that the majority of the energy being dissipated at higher shear angles due to yarn compaction. The scope of altering weave pattern and yarn characteristics is facilitated in this developed model.

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Keywords: in-plain shear; unit cell; finite element; transverse-longitudinal shear modulus.

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1. Introduction

Woven fabrics are being ever more widely used in modern industries due to their balanced mechanical properties, ease of handle and good drape-ability together with reduced manufacturing cost as compared to the unidirectional reinforcements, Dixit et.al. (2014). These are particularly suited for manufacturing of inflatable structures,

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membranes and double curved structures Cavallaro et.al (2007). Laminated composite plates generally offer good in-plane properties but are prone to delamination due to their poor mechanical properties in the thickness direction. In an attempt to overcome this drawback, woven-fabric composites, also termed textile composites, are put to use, as they offer a 3D reinforcement in a single layer and provide better mechanical properties in both in-plane and transverse directions Dixit and Mali (2013). Woven fabrics are available in different weaving pattern such as plain, twill, satin and basket weave in the dry form which further can be consolidated with matrix material (resin. etc.) via resin transfer molding (RTM) or any other manufacturing process to form a composite Boisse et.al (2007). At macro scale dry fabrics are composed of number of yarns interlaced into each other in different weaving sequences. There are usually four important levels in the manufacturing process of textile composites:

Fiber > Yarn > Fabric > Composite

Yarns at meso level can be considered as a heterogeneous media made of bundles of very thin and long fibers at micro level. The interaction and behavior of these yarns at fabric level can greatly influence the macro-level material behavior. Amongst different existing modeling approaches, meso-scopic modeling approach of woven fabrics is known and a strong tool for predicting their effective mechanical properties at macro-level.

During service, woven fabric composites are subjected to failure in tension, compression, shear and impact load. Shear deformation of woven fabric is quite complicated as it is dominated by yarn trellising/rotation at crossovers. During forming of textile reinforcement's shear is generally considered to be the primary deformation mechanism Long et al. (1996), Zouari et al. (2006). Therefore it is essential to understand fabric shear compliance for precise modeling of forming or draping processes. However during actual forming process a combined mode of the axial and shear deformation may perhaps be experienced by woven fabrics Boisse (2010). Towards this end many researchers Linberg (1961) and Lomov et al. (2008) in the past have worked on the characterization of fabric shear with the aim to determine the non-linear response of the material under shear loading and to characterize their deformation limit. The Kawabata Evaluation Systems for fabrics Kawabata (1982) and the picture frame test Guiness and Bradaigh (1998) are generally used for characterization of fabric shear behaviour in the region at small and large strain respectively. According to Lomov and Verpoest (2006) and Grosberg and Park (1996) the bending and tensile properties in various directions for both engineered fabrics and clothing are affected by and shear deformation of fabrics. However, considering the potential applications and importance of woven composites it is necessary to predict its mechanical properties with minimal possible errors. Numerous modeling schemes are available in the open literature to correctly anticipate the shear behavior of fabric but still they lack somewhere in terms of their accuracy, the level of validation and their computational efficiency. The aim of this paper is to first present a general meso-level fabric unit cell model using TexGen textile modeling schema and then after investigating its behavior under shear and combined loading mode.

2. Unit cell geometric modeling

Due to complicated weaving pattern of the yarns it is difficult to analyze the local structural behaviour of the woven fabric textile composites. For this purpose the identification of periodicity of the textile reinforcement (termed as unit cell) is a crucial which enables us to estimate the effective macroscopic properties of the textile composite by using micro mechanical methods. The effective properties comprise 3 thermo-mechanical properties like strength, stiffness, and coefficients of thermal expansion as well as thermal conductivities, electromagnetic and other transport properties. The unit cell can be considered as a periodic cube array of the fibers embedded regularly in the matrix which provides the overall behaviour of the textile composite from the known properties of the fibers and matrix phase. In the present study the unit cell which is an essential component of textile modeling is modelled using TexGen software Sherburn (2010) with the assumption that both the weft and warp yarns posses similar material and geometric properties. In TexGen yarns are treated as solid volume whose modeling depends upon numerous parameters such as yarn cross-section, yarn path and yarn surface, is handled in a systematic manner. During shear modeling the shape and size of the yarn cross sections may change which may cause yarns interpenetration, in order to avoid this TexGen creates the functions for interference correction, which adjust the textile according to yarn geometry. Figure 1 shows the schematic for balanced plain weave unit cell generated by TexGen and employed in the present study. 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.

Table 1 Unit cell size (mm)

Length	Width	Thickness	Volume
.6039	.6039	0.114	.04157

Table 2 Input data for yarn modeling

Yarn spacing	Yarn width	Fabric thickness	Number of warp yarns	Number of weft yarns
0.25	1.32	0.038	02	02

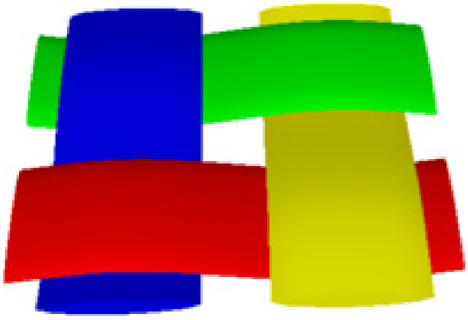

Fig. 1 Schematic of the unit cell

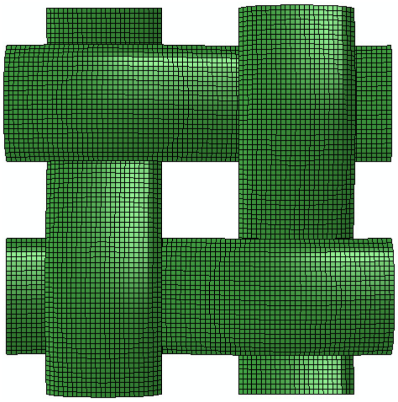

Fig.2 F.E. model of plain weave fabric unit cell

3. Material Modeling

The yarns in the present analysis are considered as an orthotropic solid body as it is not possible to simulate each and every fiber. The longitudinal direction which is parallel to fiber is defined by 11 and transverse plane is designated by the directions 22 and 33 respectively. The 3D stiffness matrix which consists of nine independent constants as shown in Eq. 1 is used to define the orthotropic behavior of the yarns. Transversely isotropic material law with non-linear transverse mechanical properties is incorporated using finite element (FE) simulation software ABAQUS®.

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

Incorporating transversely isotropic yarn behaviour the material law results in the following set of equations as shown in Eq.2.

$E_{22} = E_{33}$, $\upsilon_{12} = \upsilon_{13}$, $G_{12} = G_{13}$ and

$$G_{23} = \frac{E_{33}}{1+\upsilon_{23}} \tag{2}$$

In the present investigation the material properties of carbon fiber plain weave has been mentioned in Table 3.The elastic properties used for modeling the shear behaviour of plain weave fabric consisting of T300 carbon fibers is mentioned in Table 3.

Table 3 Material properties for plain weave (T300 carbon fiber) Mc. Bride and Chen (1997)

Fiber	Yarn per cm	Fiber density g cm^{-3}	Fiber dia µm	Fiber volume fraction %
Carbon	4.92	1.76	9	52

Table 4 Elastic properties of carbon (T300) fiber (Moduli in GPa) Sun et al. (1998)

E_{11}	E_{33}	υ_{12}	υ_{23}	G_{12}	G_{23}
220.69	13.79	0.20	0.25	8.97	4.93

3. Finite element modeling

3.1 FE implementation

FEM application in textile composites can be visualized as assemblages of representative volume elements (RVEs) or unit cells, interconnected at discrete numbers of nodal points. Now once when a geometric model of a unit cell is created using TexGen the subsequent step is the recognition of fully integrated modeling approach which has the capacity to reproduce textile models within a modeling environment automatically. For this purpose ABAQUS® is chosen among the many commercially available FE packages since this is the most fully automated modeling route. However the motivation behind using TexGen and ABAQUS in combination is that both are based on similar Python scripting interfaces, hence the required codes for linking the above two were written by the researchers of University of Nottingham which enables the reproduction of textile models within a modeling environment automatically. The python script contains the code which creates the TexGen geometric model while the outer surfaces of the yarns are defined when the program loops over the hierarchy of textile. The geometry generated by TexGen is initially saved in .tg3 file format which in turn can be exported in ABAQUS Dry Fiber File/ Voxel file environment depending upon the nature of problem. Further the generation of material definition and boundary conditions are incorporated by certain Boolean operations. The fully automated python script has the potential to take care of contact issue between the platen (if required) in case of compression, creation, submission and detailed data analysis of job. The automated modeling approach with implicit FE scheme was carried for static simulations in the present investigation. The details of FE modeling approach can be find out in the literature Sherburn et.al. (2007). The schematic of the FE model for the sheared plain weave unit cell is shown in Figure 2.

3.2 Periodic *Boundary Conditions*

It is necessary to consider the effect of adjacent cells into account as a single isolated unit cell alone is not sufficient for the true representation of the whole fabric structure. In other words, suitable kinematic or dynamic conditions must be imposed on the perimeter of the unit cell especially where it joins the adjacent cells. These conditions are termed as periodic boundary conditions. In the present study for pure shear deformation, equal displacements are applied on the opposite parallel surfaces of a yarn due to which yarns are subjected to torque, resulting in a pure rotation.

3.3 Meshing

Mesh generation has been undertaken by using C3D8R i.e. three dimension 8 noded brick element with reduced integration within the script. The coordinates of the centroid of each element within the yarns are calculated which are further passed to a TexGen function which returns the fiber orientation vector at each point. The total number of elements and the nodes involved in the analysis are 23760 and 35868 respectively. The model was found insensitive to further refinement of mesh.

4. Results and discussion

The schematic of the simulated unit cell under shear deformation is shown in Figure 3. It can be seen that intensity of the stress is of higher order in the region where yarns are subject to the lateral compression thereby generating pressure inside the yarns. During shear the fibers in a yarn have a tendency to slip relative to each other. In an experimental studies conducted by Zhu et al. (2007) it was established that intra-yarn deformation or yarn shearing also occurs during picture frame tests. The complete shear deformation process for a typical plain woven-fabric composite is shown in Figure 4 and can be explained in four different stages: Initially the yarns are orthogonal to one another and are in undeformed state. In the second stage as soon as the shear deformation initiates the yarns begin to rotate and slip over each other.

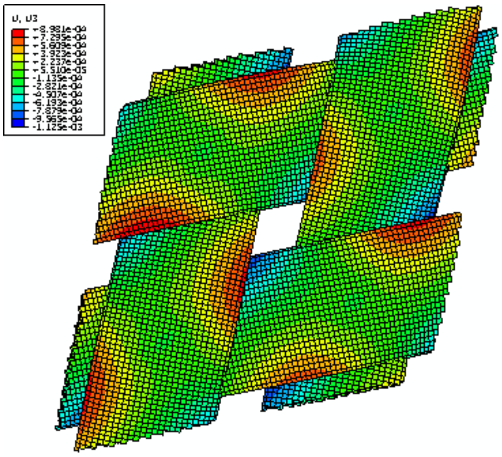

Fig.3 Simulated unit cell under shear loading (Shear angle 12^0)

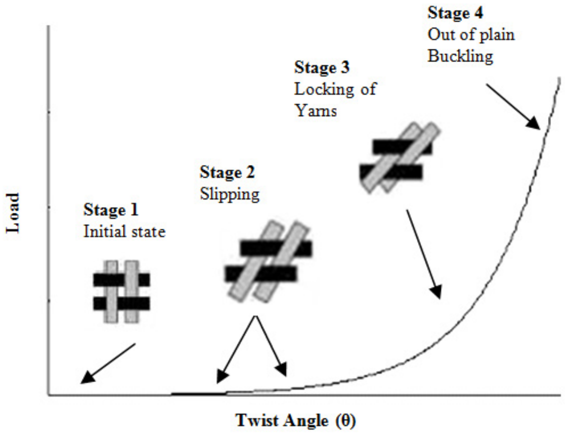

Fig.4. Shear deformation curve of a typical plain woven composite

The deformation continues until the compaction of yarns starts at a certain angle and consequently the shear stiffness increases as the adjacent yarns begin to compress each other. This process will continue up to the point when the yarns are no longer able to compact easily ie. a stage is reached where the locking of yarn occurs (refer stage 3). Now if the deformation is allowed to occur beyond the locking of yarns it will causes the fabric to buckle out of plane thereby increasing the stiffness significantly. After this point the deformation mode becomes a combination of tension, compaction and shear respectively. In order to validate the present model the maximum displacement in the third direction (U_3) is compared with the published results for glass fiber plain weave Chomarat 150TB fabric and found to be reasonable. The comparison is depicted in Table. 5 However it is expected that the results of present model to be in fairly good agreement with the ongoing experimental investigation.

During the modeling of yarns in case of shear deformation a care has to be taken, as the yarn are likely to twist, so a constant cross-section throughout the length of the yarns will no longer be valid. Hence in order to avoid intersection between two consecutive yarns it is suggested to model a yarn in such a way which twists in one direction at 1/4 of its way along the yarn length and twists in the other direction at 3/4 of the way along the length of the yarn.

Table 5 Comparison of displacement

	Present	0 et.al. (2008)
U_{3max}	9.1 e-02	8.809 e-02

The next challenge is to define a sheared domain which was achieved by specifying 6 planes which define the bounds of the domain. Figure 5 shows the representation of various energies on a time scale. Frictional dissipation (FD) can be defined as the loss of energy in heat due to friction between the yarns was initially analyzed zero at the start of shear and later attains a definite value. The strain energy within the unit cell which can be defined as the summation of energies of all elements involved in the analysis starts with zero and ends at a certain value similarly as in case of artificial strain energy and external work. Finally the internal energy in ABAQUS can be defined as the summation of artificial strain energy, recoverable strain energy, plastic dissipation energy, energy dissipated by creep, visco-elasticity and swelling also follows the previous identical curves.

5. Conclusion

The behavior of textile under shear load has been examined and verified using combination of TexGen and ABAQUS software. The generation of shear force can be attributed due to three reasons: friction at crossovers, yarns contact with each other and lateral compression. Periodic boundary conditions proved to be suitable for predicting shear force at large deformations. The shear behavior of the fabric is fundamentally dominated by the transverse Young's modulus E_{33} which is also a function of fiber volume fraction. As the strains applied to individual fibers are not represented correctly by the shear strain of the continuum element, hence no matter how accurately sliding of fiber is modeled, it is not possible to model internal stresses of the fibers accurately. Moreover a small tension reaction force was also noticed during shear deformation, even though no stretching is applied to the yarns. The model has the ability to clearly identify and process the FE analysis in those areas where fiber volume fraction is not constant. Further it is suggested that more experimental and or numerical studies/models are required to analyze and validate the shearing behavior of textiles.

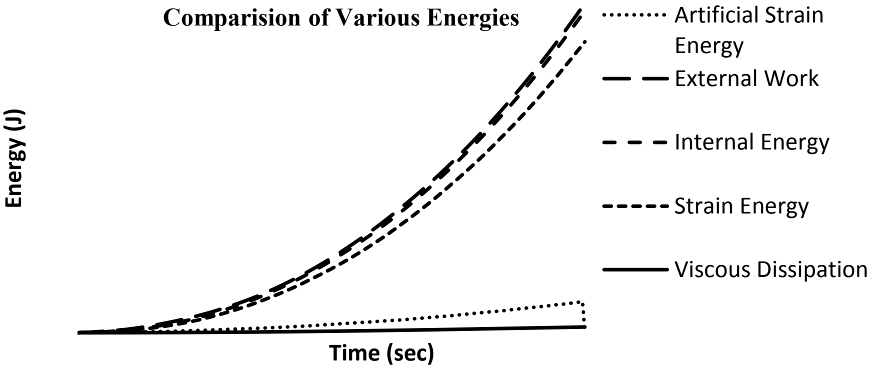

Fig.5 Comparison of various energies during shear deformation

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