

Effect of Compaction during Manufacturing of Textile Composites.

Md Shariful Islam and Pavana Prabhakar*

Department of Mechanical Engineering, The University of Texas at El Paso, TX-79902, USA

ABSTRACT

The influence of fiber tows on the deformation and damage evolution in fiber reinforced composites is investigated by considering a micromechanical model of fibers within matrix that is undergoing compaction and subsequently subjected to mechanical loads. The stresses developed due to compaction of the matrix during the VARTM manufacturing process is modeled using the finite element (FE) framework. Nonlinear material behavior due to post-damage response that can lead to cracking in the matrix is incorporated through a crack band model that preserves mesh objectivity in the FE calculations. The mechanical response of the composite along with damaging capability due to compaction and subsequent mechanical loading is investigated in detail in this paper. The influence of the curing process is not considered in this paper. But, the final quality of the composite, subjected to varying compaction, is investigated using a mesoscale model.

Keywords: Textile Composite, Damage, VARTM, Finite Element Method, Compaction.

1. Introduction

Textile composites are finding extensive use in the aerospace and automobile industry due to their high stiffness to volume ratio, easy formability and drapability[1]. For a rapid development of these materials in terms of high strength and durability, there is a need for a thorough understanding of the material state, and the influence of processing on the material response in subsequent service applications. Therefore, along with design aspects, like geometrical design and weaving, manufacturing induced defects have to be accounted for. These defects act as global failure initiation points within the composite. Therefore, in order to minimize any premature failure in the final composite manufactured, it is crucial to investigate process induced defect in these composites.

The most commonly used manufacturing technique for textile composites is the Vacuum Assisted Resin Transfer Molding (VARTM). In this technique, layers of dry fabric of the textile are placed on top of each other, and subjected to vacuum. Further, liquid resin is transferred through the dry fabric through injection tubes, and is subjected to pressure and temperature as a curing process to manufacture the composite. The effects of compaction before or during the resin infusion are that the yarn has a very complicated shape and the fiber volume fractions vary locally[2, 3]. Nesting occurs between the yarns [2-4]. Further, compaction creates complicated contact zones between the yarns [1-3] [5]. Grail et al.[6] developed a new finite element mesh generation method for textile preform and compacted reinforcement.

The inputs to the manufacturing process influence the outcome of the composite in different ways. The pressure applied to the dry fabric, the rate of resin injection, the temperature during curing, are a few processes that may alter the quality of the final laminate. Therefore, it will be useful to the industry, if there are computational tools

which are able to predict the final outcome of the VARTM process.

In this paper, the influence of the compaction on woven glass fabric during the VARTM process is investigated. In this context, the tensile response of the woven composite subjected to varying compaction is computationally studied. As a first approach, compaction on fabric layer during manufacturing and tension on the final composite was considered in this paper. Stresses developed during the curing process of resin are not considered in this paper which is under consideration as a next step.

2. Mesoscale Model

Four layers of glass fabric (as reinforcement) and Epon 638 with Epikure 9553 hardener (as matrix) was used in the paper. Fig. 1 shows the RVE with woven fiber tows and matrix. Fig. 2(a) shows a single layer of glass fabric with an exaggerated view. Geometry of the RVE was modeled with TexGen software, which is specially designed to model textile composites. The geometry of the model was then exported to ABAQUS (commercially available software) to perform the finite element analysis.

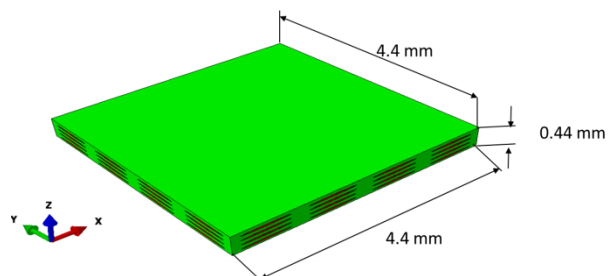


Fig.1 RVE of woven composite

The computational modeling approach is divided into two parts: 1) Compaction of the fiber tows with uncured

* Corresponding author. Tel.: +1 (915) 747-5863
E-mail address: pprabhakar@utep.edu

resin, and 2) Tensile response of the post-cured composite with damaging capability included in the matrix.

2.1 Computational Modeling of Compaction

In the compaction step, the RVE shown in Fig. 1 is used. The properties of the glass fiber used in this model are

$E_f = 85$ GPa and $\nu_f = 0.22$. For the compaction model,

it is assumed that the liquid resin fills the entire space between the dry fabrics. Therefore, prior to solidification of the resin, it was considered that 5 % of the resin has already cured. The matrix properties at this stage are $E_m = 0.081$ GPa and $\nu_m = 0.48$ [6]. The homogenized tow properties were calculated using these properties of fiber and matrix using the concentric cylinder model[7]. Table 1 shows the homogenized properties of tows in the uncured state.

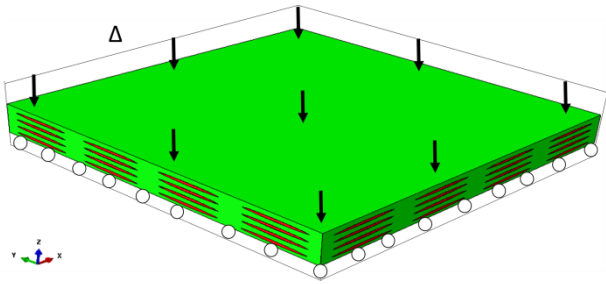


Fig.2 Boundary Conditions for Compaction Modeling

The boundary conditions used in the compaction modeling are shown in Fig. 2. Displacement of the bottom surface was restricted in the z-direction, and a displacement condition simulating a compaction was applied on the top surface. All other faces were maintained to be flat, i.e. the faces all allowed to breathe while remaining flat. Five different compactions, i.e. 5%, 7.5%, 10%, 30% and 50% of the thickness of composite were considered to study the effect of compaction of the final composite.

Table 1 Homogenized Tow Properties with 5% cured Matrix.

E_{11} (GPa)	$E_{22}=E_{33}$ (GPa)	$\nu_{12} = \nu_{13}$	ν_{23}	$G_{12}=G_{13}$ (GPa)	G_{23} (GPa)
51.03	0.254	0.307	0.24	0.111	0.105

2.2 Tensile Modeling of the Compacted Composite

The models corresponding to the different compaction values are subjected to tensile loading post-cure. As mentioned above, the curing process is not modeled in this paper. Therefore, the cured matrix properties were considered for the tensile loading step. That is, the cured

matrix properties are $E_m = 4.95$ GPa and $\nu_m = 0.375$ [6].

Table 2 shows the corresponding homogenized tow properties. Boundary condition for this case is shown in Fig. 3. Flat boundary conditions mentioned used for the

compaction step was used for free surfaces in this current step as well.

Table 2 Homogenized Tow Properties of Final Composite

E_{11} (GPa)	$E_{22}=E_{33}$ (GPa)	$\nu_{12} = \nu_{13}$	ν_{23}	$G_{12}=G_{13}$ (GPa)	G_{23} (GPa)
53.01	13.67	0.375	0.25	6.044	5.468

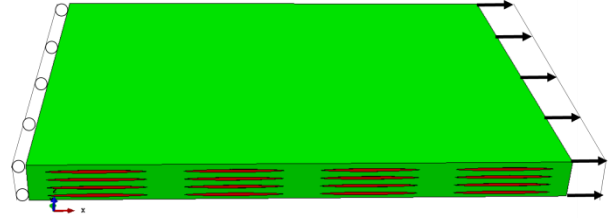


Fig.3 Boundary Conditions for Tension Modeling.

2.3 Damage Capability in Matrix: Crack Band Model

Including damage capability in materials adds a region with negative tangent stiffness to the constitutive law. Classical finite element method (FEM) converges to a single solution with mesh refinement, as long as the tangent stiffness of the constitutive law is greater than or equal to zero. But, a negative tangent in the constitutive law makes the model pathologically mesh dependent. That is, the results change as the element size is reduced. Therefore, the energy dissipated during the failure process has to be scaled with the element size to make the problem mesh objective. Crack band model (CBM) introduced by Bazant and Oh [8] is an efficient method to account for the element size during material damage.

The damaging regime is modeled by adding a traction-strain law beyond a critical strength value in the constitutive law. The traction-strain law is determined by converting a traction-separation law utilizing the characteristic element length " L_c " as shown in Fig. 4. The two inputs to the traction-separation law are the cohesive/critical strength (σ_c) and fracture toughness (G_c) of the material.

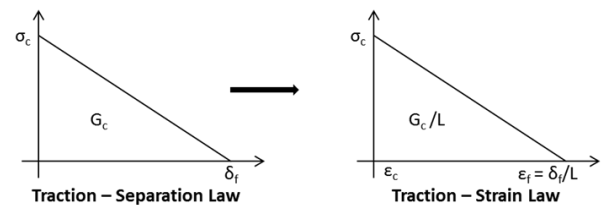


Fig.4 Converting traction-separation law to traction-strain law.

In CBM, a typical stress-strain material law is generated by adding a linearly decreasing damage path, with the characteristic length included, to follow the initial linearly increasing regime as shown in [8]Error!

Reference source not found.. The initial linear stiffness of the material is “ E ”, which is a function of the degree of cure. As the strain within an element in the FEM model exceeds the critical strain corresponding to the critical stress, the stiffness of the element is reduced accordingly by entering the damage path in [8]**Error! Reference source not found..** The degraded stiffness value is determine as $E = \sigma_i / \epsilon_i$, corresponding to the strain in the element.

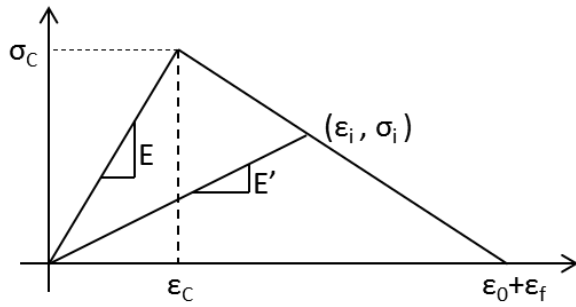


Fig.5 CBM: modified stress-strain material law incorporating failure.

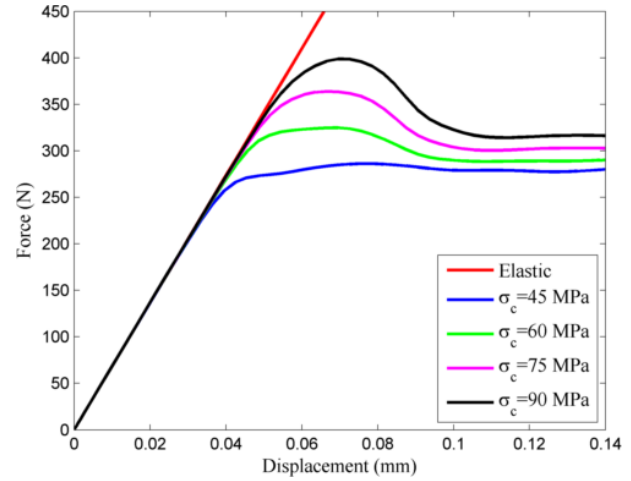
3. Results and Discussions

For the compaction modeling, 5 different displacements for compaction were used, i.e., 5%, 7.5%, 10%, 30% and 50% of the thickness of the composite (in the z-direction). Table 3 shows the original and deformed dimensions because of compaction. Here, the original length of the RVE is $L = 4.4\text{mm}$, and the thickness $t = 0.44\text{mm}$, the corresponding dimensions after different compaction are given in the table.

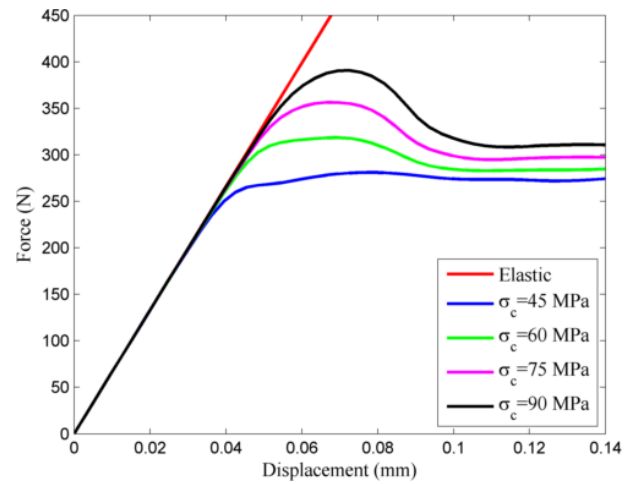
Table 3 Original and Deformed Dimensions after Compaction.

Model	L (mm)	t (mm)
Original	4.4	0.44
5 % Compaction	4.40564	0.418
7.5 % Compaction	4.40846	0.407
10 % Compaction	4.41128	0.396
30 % Compaction	4.43383	0.308
50 % Compaction	4.45638	0.22

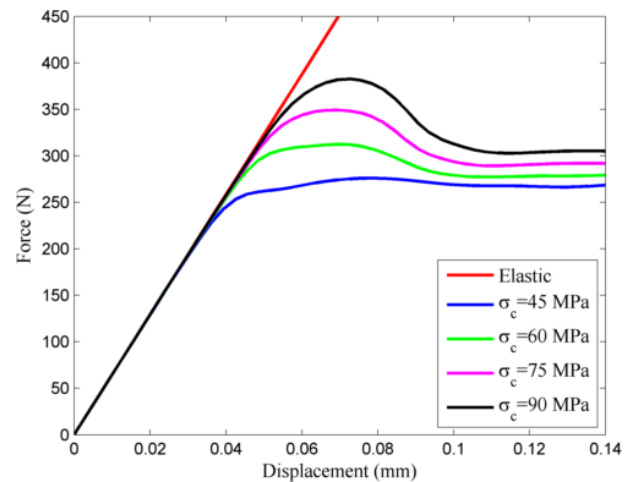
Fig. 6 shows the load-displacement diagrams for tensile response for different compaction and varying critical stress values (σ_c) for the matrix. The initial stiffness for 5%, 7.5% and 10% compaction is almost same for all values of, but this stiffness reduced because of more compaction (30% or 50% compaction). So, the amount of compaction plays an important role on the initial stiffness of the final composite. Fig. 6 also shows that the global tensile failure load decreases with increase in compaction.



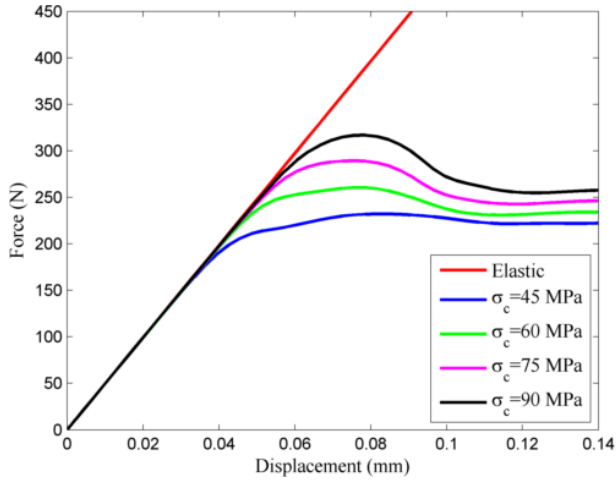
(a)



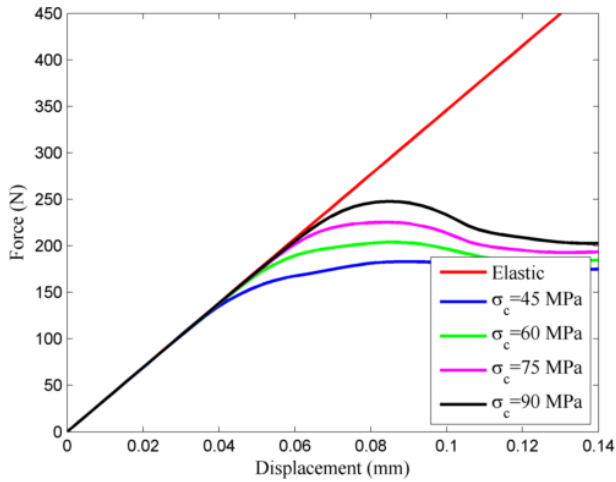
(b)



(c)



(d)

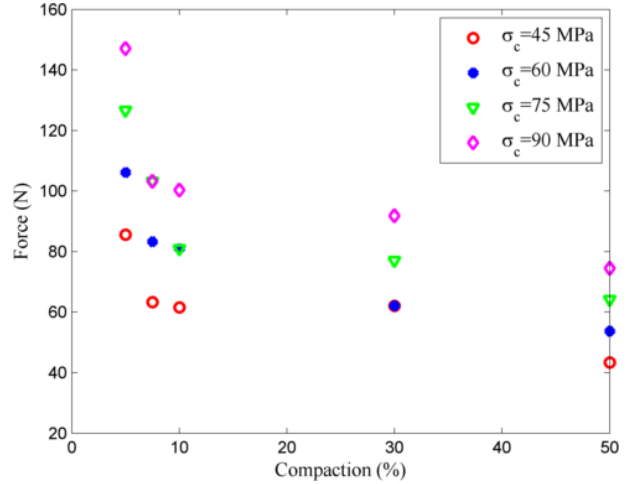


(e)

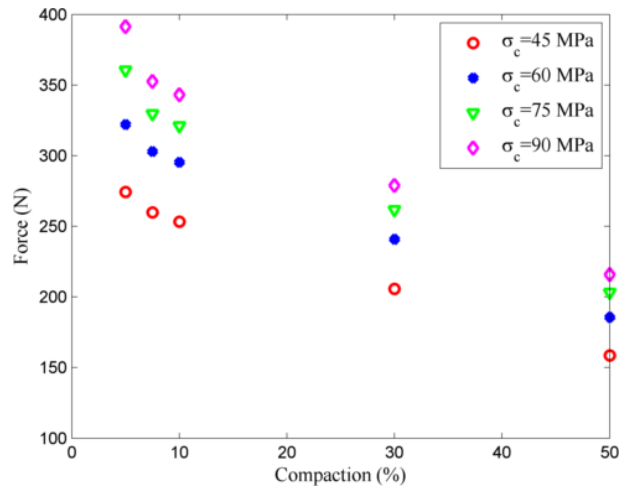
Fig.6 Load Displacement Response corresponding to Varying σ_c at Different Compactions of (a) 5%, (b) 7.5%, (c) 10%, (d) 30%, and (e) 50%.

The tensile load corresponding to first damage initiation in the composite is plotted in Fig. 7(a) for varying compaction and σ_c values. It is observed that the loads reduce with increasing compaction and reducing σ_c . similar behavior is observed for tensile loads at first failure points for different compaction and varying σ_c in Fig. 7(b). Fig. 7(a) and Fig. 7(b) indicate that when the compaction is increased from 5% to 50%, the loads for damage initiation reduces by 50%, and for the first failure point reduces by approximately 43%. For illustration, the damaged and the failed regions in the

composite for 5% compaction and $\sigma_c = 45$ MPa, are shown in red in Fig. 8(a) and Fig. 8(b). This indicates that the composite with greater compaction during manufacturing will fail prematurely when subjected to service loads.

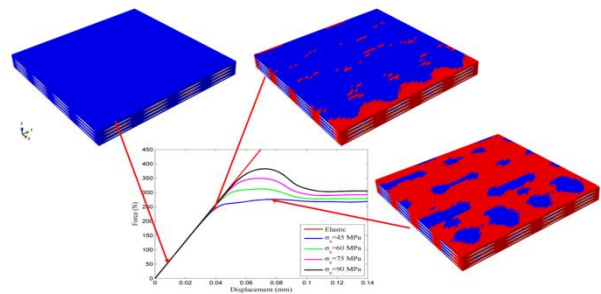


(a)



(b)

Fig.7 Loads at (a) First Damage and (b) Failure Points.



(a)

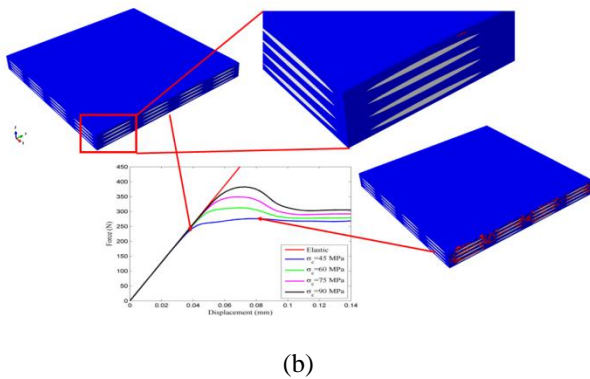


Fig.8 Example of Damaged and Failed Regions;
Compaction = 5% and $\sigma_c = 45\text{MPa}$

4. Conclusions

The effect of compaction during manufacturing of woven fabric composite by VARTM process is investigated in this paper. The damaging capability of matrix included in the finite element model by means of crack band model which preserves the energy dissipated during the failure process with varying element size and hence reduces the mesh sensitivity of the finite element analysis. The stresses developed during the curing process is not considered in the present paper, but it will be considered in the future work.

NOMENCLATURE

- E_f : Stiffness of fiber, GPa
 E_m : Stiffness of matrix, GPa
 ν_f : Poison's ratio of fiber
 ν_m : Poison's ratio of matrix
 G_c : Fracture toughness of matrix
 σ_c : Critical stress of matrix, MPa
 L : Length of RVE, mm

REFERENCES

1. Mouritz, A., et al., *Review of applications for advanced three-dimensional fibre textile composites*. Composites Part A: Applied Science and Manufacturing, 1999. **30**(12): p. 1445-1461.
2. Olave, M., et al., *Internal geometry variability of two woven composites and related variability of the stiffness*. Polymer Composites, 2012. **33**(8): p. 1335-1350.
3. Karahan, M., et al., *Internal geometry evaluation of non-crimp 3D orthogonal woven carbon fabric composite*. Composites Part A: Applied Science and Manufacturing, 2010. **41**(9): p. 1301-1311.
4. Chen, B., E.J. Lang, and T.-W. Chou, *Experimental and theoretical studies of fabric compaction behavior in resin transfer molding*.

Materials Science and Engineering: A, 2001. **317**(1): p. 188-196.

5. Lomov, S.V., et al., *Nesting in textile laminates: geometrical modelling of the laminate*. Composites Science and Technology, 2003. **63**(7): p. 993-1007.
6. Heinrich, C., et al., *Generation of heat and stress during the cure of polymers used in fiber composites*. International Journal of Engineering Science, 2012. **53**: p. 85-111.
7. Hyer, M. and A. Waas, *Micromechanics of linear elastic continuous fiber composites*. Comprehensive composite materials, 2000. **1**: p. 345-375.
8. Bažant, Z.P. and B.H. Oh, *Crack band theory for fracture of concrete*. Matériaux et construction, 1983. **16**(3): p. 155-177.