PARAMETRIC NUMERICAL SIMULATION OF COMPOSITE REINFORCED BY KNITTED FABRIC

Umesh-Haribhai Vavaliya
Riga Technical University, Latvia
umesh-haribhai.vavaliya@rtu.lv

Abstract. Research in parametric analysis based on numerical simulation of composite materials reinforced by weft-knitted fabric is carried out. The aim of this research is to predict the mechanical properties of the composite by experiments and the SolidWorks simulation within given assumptions and boundary conditions. The yarns were impregnated with epoxy solution and dried in further process for the experiment. The impregnation process helps control the fiber-resin ratio. The different fiber volume fraction is tested to see the effect of impregnation on the elasticity of the composite. The same analysis is done on three different composites, Carbon yarn (230 GPa), Steel yarn (210 GPa), and Hybrid Carbon- Steel yarn as reinforcing material and Epoxy(4 GPa) as the matrix material. Leaf and Glaskin models were used to create a loop structure of the knitted fabric. To reduce the complexity and overall computational time, a generalized structure called the unit cell is created for the entire model due to the symmetrical shape of loops. The numerical simulation is done in transverse directions by fixing the geometry on one side and applying displacement on the other side. Composites were tested by tension experimentally (ASTM D3039 standard method) and numerically (Finite element analysis) until fracture of the fiber structure. The maximum value of stress is taken into consideration for both principal directions. Simple Hooke's law was used to calculate elasticity and eventually other mechanical properties of the material. The effect of single and multi-thread on the elastic properties of composite materials was determined. The results of elasticity for the different values of fiber volume fraction of 0.1 to 0.5 were determined and compared with the experimental data. The obtained results are in great agreement with the experiment data.

Keywords: knitted fabric, elastic modulus, rule of mixtures.

Introduction

Textile reinforced composites making their way to different engineering fields is now very commonplace. The usage of such materials in various structures is trending due to their high strength, high stiffness, and low density behaviour [1]. Textile reinforced composites are now replacing traditionally used metallic materials due to their wide range of applications in aeronautics, space, automotive sectors. Composite materials with textile reinforcement typically have fabrics of textile as reinforcement and usually polymers as matrix materials. However, some promising studies also use some brittle matrix (concrete, ceramics) with knitted fabric as reinforcement to investigate mechanical properties of such composites [2-4]. 2D and 3D weaved fabric, knitted fabrics, braids, multiaxial fabrics are some common textile reinforcements [5]. 2D woven fabric consists of two sets of yarn weaved by conventional weaving technology in the longitudinal and transverse directions. However, the research found that such fabrics have low fatigue and stiffness resistance characteristics when applied to shear stress [6]. 3D textile reinforced consists of improved mechanical properties with high impact resistance and damage tolerance [7].

Recent increase in the interest of the textile reinforcement field is seen in knitted fabric reinforcement. Such fabric can be made by looped yarn in rows usually called "courses" and in columns which are called "wale." Such loop structure can be used to form complex shapes without having any flanks. This loose structure of looped materials allows the fabric to have large stretch deformation properties to adjust the complicated shapes [8; 9].

Generally, two types of knitted fabrics are utilized for reinforcement – Weft, and Warp. Weft knit involves the formation of loops in a flat horizontal direction from a single strand of yarn. While the Warp knit is created by interlinking loops on a lateral array of needles in an axial direction having each loop made from a different strand of yarn. Weft knitted is more preferred due to its simple formation of loops with higher formability. Mechanical properties through the thickness of knitted fabric composites are comparably higher than unidirectional fiber structured composites such as woven and braided fabric composites because fibers in knitted are oriented in the in-plane and thickness directions. [10]

The goal of this paper is to investigate weft-knitted textile-reinforced composite having different ratio of resin to fabric. Multiple studies analyzed the geometrical representation of the looped structures of weft knitted fabric: models of Leaf and Glaskin [11], Kawabata [12], Munden [13], and Choi [14].

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However, Leaf and Glaskin model was used to investigate further. Carbon fibers are one of the oldest and commonly used high-strength fibers in composite production. Carbon threads and steel threads are used for the preparation of weft knitted fabric. A hybrid fabric using both threads was also prepared. The results of elastic modulus derived from numerical simulation and experimentally are compared.

Method of Research

Leaf and Glaskin Model was used to make the geometric model of the thread in the knitted fabric. Leaf and Glaskin (1995) [11], claimed that three primary parameters can create the structural geometry of the thread. First, the wale number *W*, which can be described as the step of fabric's loops per unit length along the width (in the course) direction. Second, the course number *C*, the step along the length (in the wale direction), and third, the diameter *d* of the thread.

MATLAB code was used to get the X, Y, Z points of the thread curve, which is then inserted in SolidWorks software to generate the geometrical curve passing through the points [15]. A symmetrical and repetitive pattern can be seen in the thread geometry as shown in Fig 1a. We can reduce the overall complexity of the simulation and use of computational power by creating a Unit cell, i.e., the smallest repeating sub-structure of an entire fabric geometry. Numerical simulations were performed on the 3D unit cell.

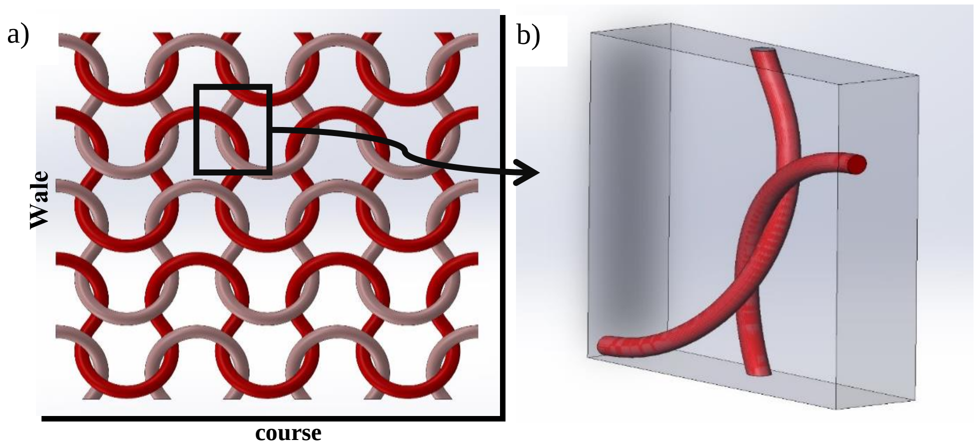

Fig. 1. **Knitted fabric geometry (a) unit cell of the model used for simulation (b)**

Material and Structure use

Three different SolidWorks simulations were carried out for three different materials in the longitudinal X and transverse Y directions. Certain assumptions were considered about the internal surface of the fabric for the simulation [7; 16; 17]. Yarn of the different materials is considered as a homogeneous elastic rod with the same diameter across its length. Epoxy is chosen as a matrix material with 3 GPa of elastic modulus with linear elastic isotropic properties. An independent simulation of two different reinforcements – Carbon T300 and SY11 Steel Yarn was carried out. A hybrid composite of Carbon T300 and SY11 steel yarn as reinforcement and epoxy as matrix is also created and simulated in the same boundary conditions. The material properties taken in the simulation are given in the table.

Table 1

Material properties of composite

Materials	Elastic modulus, GPa	Poisson ratio	Density, kg·m^{-3}	Yield strength, MPa
Carbon T300	230	0.20	1020	3530
SY11 Steel	210	0.28	7700	620
Epoxy	4	0.35	1180	30

3D curve was generated by importing the X, Y, and Z points for the first and second threads using equations from the Leaf and Glaskin Model [11]. As stated above, we need three primary parameters the wale number *W*, course number C and the diameter of the yarn *d*, to get the geometrical representation of the yarn. Parameters taken for the current study are given in Table 2.

Basic SolidWorks functions were used such as Spline, Sweep, Extruded cut function to create the geometry shown in Fig 1. A cube shape matrix was created that covers both ends of threads. Hollow loops for the thread assembly were created accordingly. Finally, the matrix and yarn were assembled as a composite in SolidWorks assembly [15].

Mesh and boundary conditions are applied in SolidWorks. Bonded contact without penetration was applied since the matrix and yarn are in constant touch. Front, left, and down faces were fixed as roller sliders, which permits in-plane movements but restricts normal to plane movements. Instead of applying force, surface displacement of 0.001mm is given on the top face normal to the top plane for transverse direction. Since the created unit cell was small, selection of the mesh type and size is crucial. The fine mesh was generated with 0.02 mm of maximum element size to get accurate results. Fig 2. shows the mesh and boundary condition.

a) b)

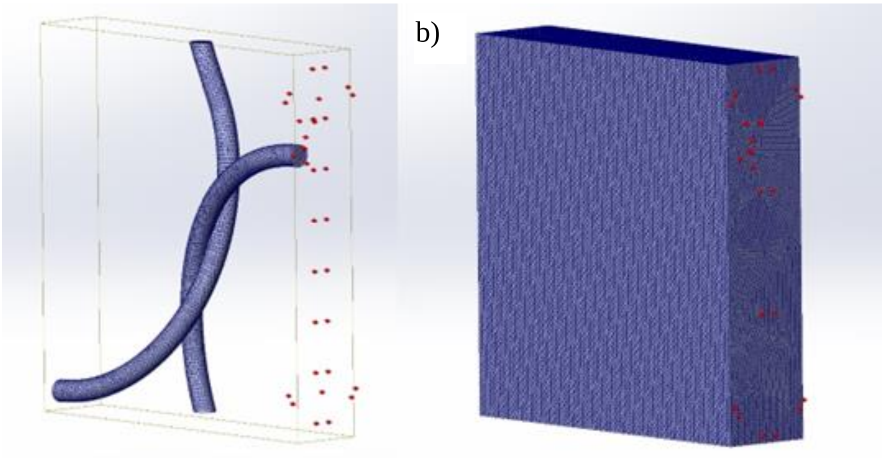

Fig. 2. **Mesh in yarn (a) and mesh in unit cell (b)**

Experiment and result

Weft knitted fabrics made of Carbon T300 and Stell SY11 yarn were manufactured in the Riga Technical University Lab and tested in a tensile test machine to investigate the elastic properties. A standard method of ASTM D3039 tensile testing was used. The knitted fabric was embedded in matrix resin (epoxy resin in our case), this process is also known as the impregnation of fiber. The resin impregnation method helps control the fiber to resin ratio and thickness of ply. Wang F. et al [18] studied the fiber matrix impregnation behaviour and found that increase in impregnation percentage improves the tensile strength and elasticity of the composite.

In the curing stage, the excessive resins are removed in an autoclave under pressure and temperature. Fabrics were dried and cut accordingly. This pre-preg was tested in the Riga Technical University Lab. When the experiment was carried out on the lab. composite, the fiber volume fraction was found to be 0.3. The experimental results of the tensile test in the transverse direction are given below in the table.

Table 2

Experiment results and parameters

Materials	**Elastic modulus, GPa**	**Wale number *W* loops per cm**	**Course number *C* loops per cm**	**Diameter of yarn mm**
Carbon T300	13.41	2.25	5.60	0.022
SY11 Steel	6.14	2	5	0.012
Hybrid	11.09	2.5	5	0.012-0.022

Finite element method and results

SolidWorks simulation is used as the finite element method to investigate the elastic properties of epoxy/carbon and epoxy/steel fiber composite materials. To get the accurate result, the rule of mixture is used to predict the elastic constants. Rule of mixture is the simplest method to derive the elastic properties of composite materials [19].

$$E_c = E_f V_f + E_m V_m \qquad (1)$$

where V_f and V_m – volume fractions;
E_f, E_m and E_c – elasticity of the fabric, matrix, and composite respectively.

For the impregnated yarns, the value of E_c is taken as the value of E_f when the same impregnated yarn is used to make the composite. The thickness of the model taken in the experiments is different than that taken in SolidWorks simulations. It is because the SolidWorks geometry is created by using the Leaf and Glaskin Model which approximates the curve and geometry of the yarn in the loop, whereas the experimental composite uses impregnated fibers in composite having various fiber volume fraction. Also, in reality, yarn of carbon fiber and steel fiber do not have the same diameter across the length. Due to this difference in geometry and thickness, it is important to take into consideration the correct value of volume fractions for the fiber and matrix. By applying the rule of mixture, the value of elastic modulus of the matrix is estimated and applied in SolidWorks material properties for the simulations.

Since the fibers were impregnated with epoxy, various fiber volume fractions of 0.1, 0.2, 0.3, 0.4, and 0.5 are taken into the consideration and the simulation is done for all these fractions.

Here are the results of the elastic modulus of composite with various fiber volume fractions.

Table 3

SolidWorks results

Materials	Fiber volume fraction V_f	Elastic modulus, GPa
Carbon T300	0.5	18.68
	0.4	15.8
	0.3	13.03
	0.2	10.13
	0.1	8.96
Stell SY11	0.5	7.72
	0.4	6.93
	0.3	6.12
	0.2	5.31
	0.1	4.49
Hybrid Carbon/Steel	0.5	14.36
	0.4	12.51
	0.3	10.64
	0.2	8.79
	0.1	6.77

As noticed from the above table, a higher value of the fiber fraction gives a higher value of the elastic modulus for the respective composites. It is simply due to the fiber carrying partially stress when applied in tension. Due to the higher fiber volume fraction, stress can be easily distributed which increases the overall elastic modulus of the composite.

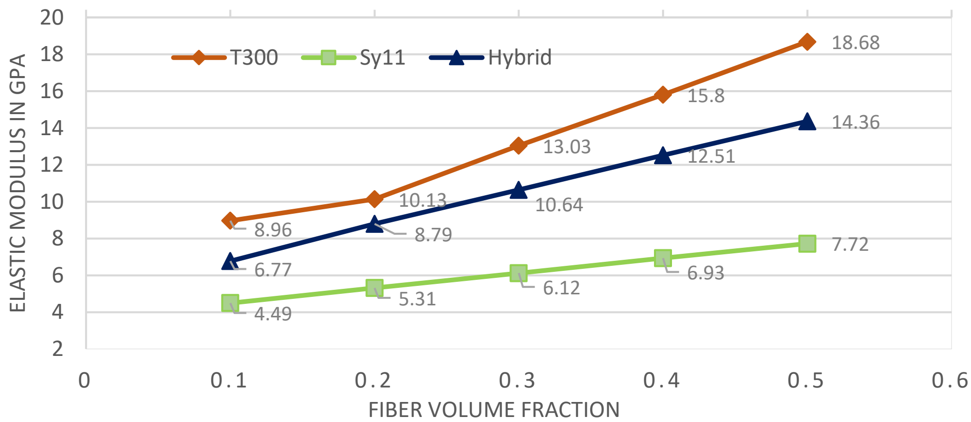

Fig. 3. **SolidWorks results of composites: elasticity v/s fiber volume fraction**

Fig 4. shows the comparison of the results of SolidWorks and experiments at 0.3 fiber volume fractions. The result of the elasticity shows good agreement.

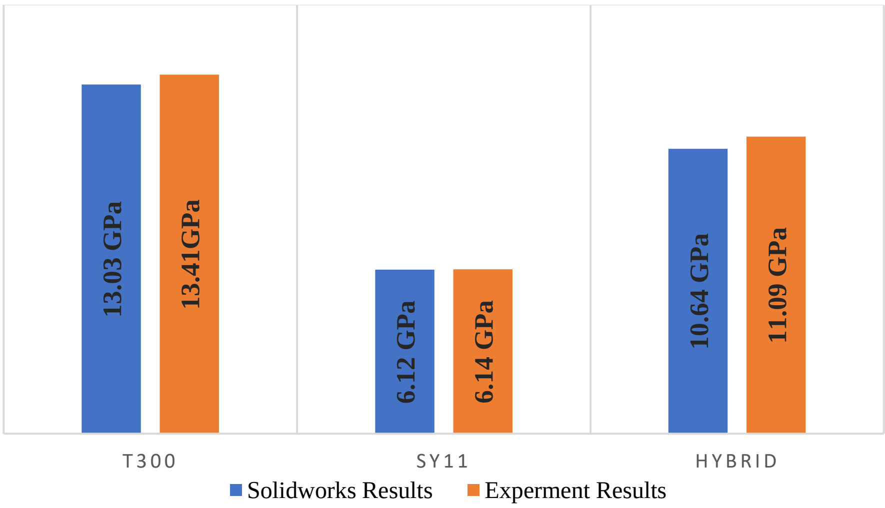

Fig. 4. **Comparison of results (SolidWorks v/s experiments)**

Conclusions

The present work covers the details of the research on epoxy/carbon and epoxy/steel fiber composites to determine the elastic modulus using the finite element method. Here are some observations from the study.

1. The results of the elastic modulus from the SolidWorks simulation are in good agreement with the experimental results done in the Lab. The results were compared for 0.7 matrix volume fractions and show a similar value of elasticity for all the composites.
2. Epoxy/Carbon composite has the highest elasticity of 13.41GPa experimentally and 13.03GPa by SolidWorks simulation. Steel SY11 with the epoxy composite has the value of 6.14 GPa. The hybrid T300/Sy11 composite shows the elasticity of 11.09GPa experimentally and 10.64GPa with simulation. Surprisingly, the hybrid composite has lower elasticity than the carbon composite. This is because before performing the experiments, all yarns were impregnated with epoxy solution. We can claim that during the process of impregnation, carbon absorbs more epoxy resins than SY11 steel yarn. This also proves why SY11 composites have nearly 50% less value of elasticity than carbon T300.

Acknowledgments

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