N. Linking Process-Induced Properties to Thermoplastic-Matrix Woven-Fabric Composites Performance

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Contractor: University of Massachusetts Lowell
National Science Foundation Contract No. DMI-0522923, jointly funded by NSF and DOE

Introduction

Modeling of the in-service performance of thermoplastic-matrix woven-fabric-reinforced structural composites – e.g., damage tolerance, crashworthiness, vibration – is currently inadequate for parts of any geometric complexity because of the inability of existing performance models to capture the true deformed material properties. As a result, lightweight composite materials are utilized inefficiently or not at all; alternatively, extensive experimental trial and error or design of experiments must be conducted to develop a satisfactory product. The key to addressing this barrier is to provide a direct link between part geometry, material selection, process conditions, process-induced local properties, and part performance, allowing informed feedback to the design process.

Fiber-reinforced thermoplastic composites have a variety of applications including structural components in automotive, aerospace, marine, infrastructure and recreation industries. The main advantage of these composites over metals is their high specific strength. They also have other beneficial properties including low thermal expansion and good corrosion resistance when compared to metals. Woven fabrics offer many other advantages when compared to metals in terms of deformation capabilities, including dimensional stability, good conformability, and deep-draw shapability. Compared to nonwoven-fabric composites, the woven-fabric composites provide more balanced properties, higher impact resistance, easier handling and lower fabrication cost, particularly for parts with complex shapes.

The objective of this research is to utilize an integrated analytical, experimental, and numerical effort to attain a fundamental understanding of two governing physical phenomena – interlayer (fabric-fabric) friction and interconnected through-thickness and in-plane compaction. The former is important in multiple-layer and multiple-step forming, both needed for industrial processes. The latter is a critical factor affecting the final part thickness, void content, fiber orientation, and fiber distribution – all are important for structural stiffness and damage tolerance. To validate and further demonstrate the capabilities of the integrated structure-process-performance design tool, the model will be used to identify critical process and material parameters for one particular performance model – damage tolerance. The funding for this research has only been available for six months, so the results reported here are very limited.

In Section 2, a combined inter-tow friction model, developed in a previous NSF-funded research program (DMII-0331267), based on the equilibrium equations of the unit cell of a balanced plain-weave glass/polypropylene woven fabric is extended to account for fiber compaction. To accomplish this extension of the model, fiber-compaction experiments have been completed and the results are reported here.

In Section 3, the design of a 3rd-generation friction-testing apparatus is presented. Previous research efforts used a constant-displacement control device to load the undeformed fabrics during the friction testing. While the information learned in these tests was invaluable in developing a fundamental understanding of the tool-fabric behavior, the 3rd-generation friction-testing apparatus will be a load-control device and will yield an even deeper fundamental understanding of the friction mechanisms by being able to study inter-layer friction between fabrics and tool/fabric friction on undeformed and deformed fabrics.

Analytical Modeling of the Shear Behavior of Woven-Fabric Composites

Trellis shear is considered the main deformation mode during the stamping process of woven-fabric composites [1]. Thus, the formability of woven-fabric composites is primarily a function of the shear properties of the woven fabric. Therefore, analytical models to obtain the shear properties of woven-fabric composites are very important for using the finite-element method for the modeling of the thermostamping process and for the designing of new fabrics.

A unit-cell model, which included (1) the key shear-deformation-resistant mechanisms, (2) the friction between the warp and weft yarns at every crossover, and (3) the lateral compaction between adjacent yarns, was developed by Liu *et al.* [2,3] to predict the shear properties of woven fabrics for the thermostamping process. In the model, some yarn parameters such as the yarn-to-yarn coefficient of friction μ, the fiber contact frequency ratio β, and the ideal maximum fiber volume fraction V_a, were chosen to develop an empirical model to fit the experimental data. Validation of those parameters is necessary to complete the unit-cell model.

The maximum yarn-fiber volume fraction V_a is an ideal limit to which fibers in a yarn can be compacted. As the yarn-fiber volume fraction approaches this maximum value, the stiffness in the transverse direction increases dramatically to approach the stiffness of the solid fiber material. According to the packing theory of uniform sizes of fibers, square packing corresponds to V_a of $\pi/4$ (or 0.785), and hexagonal packing results in a value of $\sqrt{3}\pi/6$ (or 0.907). Because the diameters of the polypropylene and glass fibers are different in the commingled polypropylene/glass yarn, the square packing theory is modified for the commingled fibers, and the obtained V_a equals to 0.813 [4].

In the plane-strain compression tests, 50-mm-long fiber bundles were placed in the channel fixture as shown in Fig. 1. A compressive force was applied perpendicular to the axial direction of the fibers (call this the z direction) using an Instron machine at a rate of 0.042 m/sec. Load and extension data were logged on a data-acquisition computer so that stress and strain in the z direction could be calculated. Because the transverse compliance can be also calculated in the fiber bundle model as a function of β, regression of the experimental data will give the mean value of β. In Fig. 2, the predicted and experimental values of the yarn transverse compliance S_{22} are compared for various values of β. The experimental results are obtained from the plane-strain compression tests for five layers of yarns as described by [5]. From Fig. 2, it can be seen that the values of β are in the range from 150 to 175 for the commingled polypropylene and glass yarns.

To investigate the sensitivity of the model to the yarn input parameters such as the maximum fiber volume fraction V_a, the fiber contact ratio β and the yarn-to-yarn coefficient of friction μ, a parametric

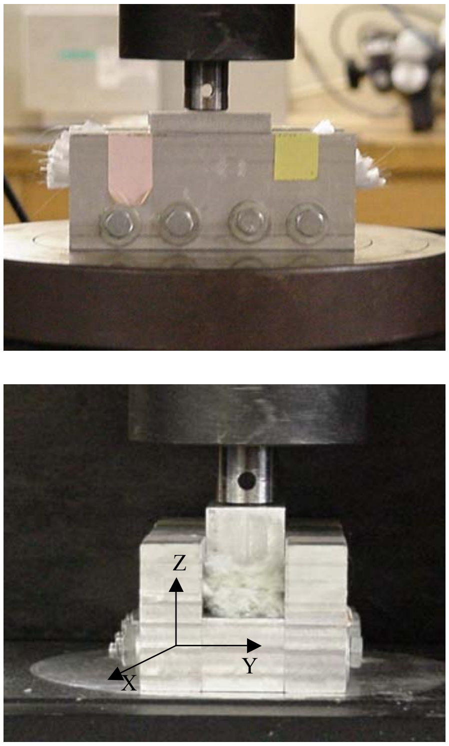


Figure 1. Plane-strain compression test fixture [5].

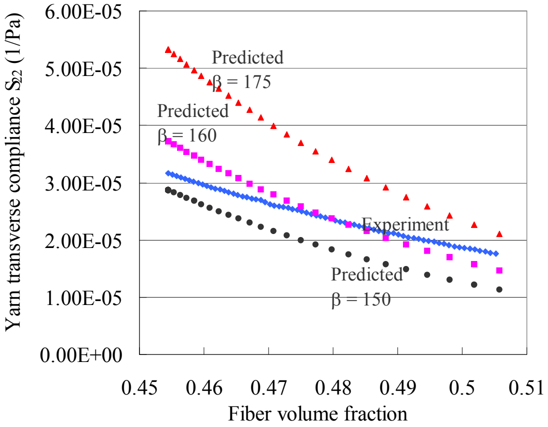


Figure 2. Comparison of the values of S_{22} obtained from the plane-strain compression tests and the fiber bundle modeling [5].

study was conducted. To separate the individual contributions from friction and lateral compaction, intermediate models were studied separately, i.e., the lateral compaction resistant moment was set to be zero to study the coefficient of friction, while in the study of β and V_a, the friction resistant moment was set to be zero in the equilibrium equation.

Fig. 3 shows the results of the simulation of β varying from 150 to 175. In the figure, it can be seen that as the value of β decreases, the shear load increases. The loads increase because at relatively low values of β, the yarn stiffness in the transverse direction increases due to increased fiber bending. As shown in Fig. 4, decreasing the value of V_a has a similar effect because, with relatively low values of V_a, yarn stiffness in the transverse direction increases due to decreased space for compaction.

Thus, with the main parameters all validated, the developed analytical model can be used to predict the shear properties of woven-fabric composites and reduce or eliminate the need for curve fitting of fabric-level experimental data.

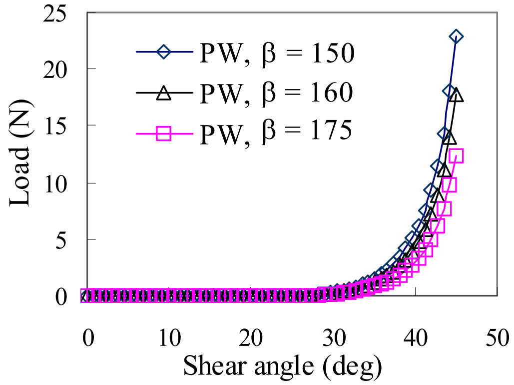


Figure 3. Simulation of the fiber contact frequency ratio.

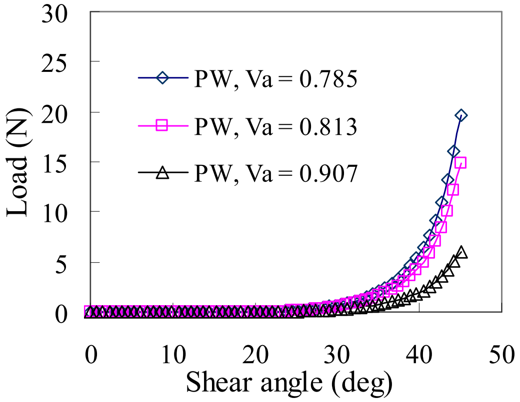


Figure 4. Simulation of the maximum fiber volume fraction.

Friction Behavior Composite between the Metal Tool and the Woven-Fabric and Inter-Layer Shear

Past research has led to advances in a user-defined friction subroutine for use in finite-element applications. The Stribeck curve (Fig. 5 [6]) and the Hersey number, *H*, (Eqn. 1) were used to predict the friction coefficient for the ranges of velocities and normal forces studied.

$$H = \frac{\eta \cdot U}{N} \qquad (1)$$

where η is the viscosity, *U* is the fabric velocity and *N* is the normal force.

The results of the study conducted by Gorczyca [7] showed that the velocity of the fabric, tool temperature, and applied normal force have the greatest effects on the friction coefficient. From these results she developed a model that relates the friction coefficient to the Hersey number, shown in Eqn. 2:

$$\mu = (6.1191 \cdot H + 0.2718) - \mu_\upsilon \qquad (2)$$

where μ_υ is a scaling term included for the effects of the tool temperature.

The results from testing such fabrics will be analyzed for their applicability to the relationship between the coefficient of friction and the Stribeck curve, as developed by Gorczyca [7,8] and Chow [9]. The design of a 3rd-generation friction-testing apparatus aims to overcome past limitations, and to enhance the characterization of not only the commingled glass-polypropylene plain-weave fabric, but also other types of fabrics involved in an international benchmarking study, as shown in Fig. 6.

Previous research focused on the static coefficient of friction [7-9]. The method of normal force application used in that research was displacement controlled. It was found that during a typical friction test the normal force applied to the fabric surface decreases, as shown in Fig. 7.

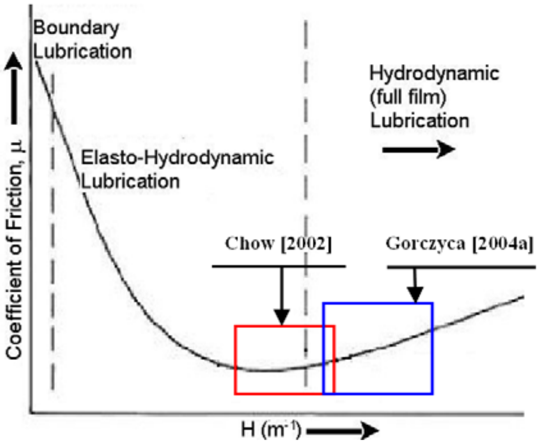
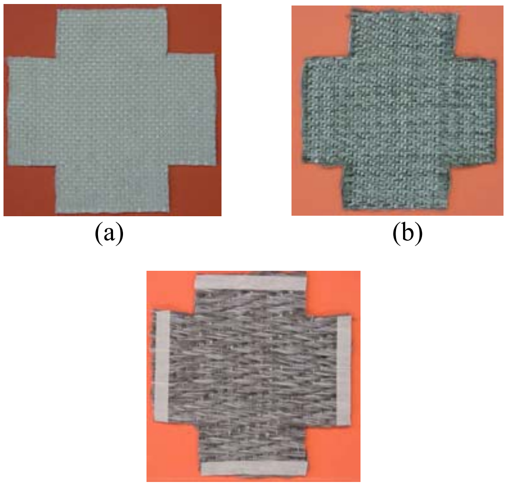


Figure 5. The Stribeck Curve and areas of interest pertaining to current research [6].



(a) (b)

(c)

Figure 6. Fabric used during international benchmark activity: (a) Balanced plain weave (PW); (b) Balanced twill weave (TW); (c) Unbalanced twill weave (UTW).

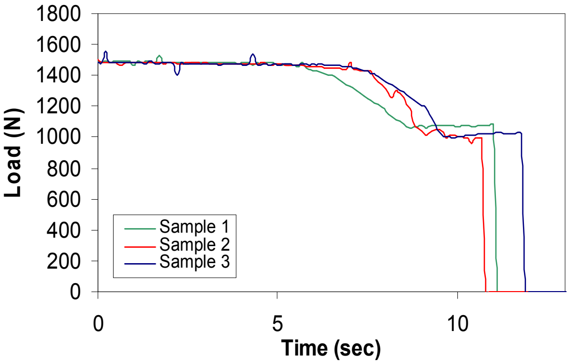


Figure 7. Normal force decrease over time for displacement controlled test of commingled glass-polypropylene plain-weave fabric.

For the tests shown in Fig. 7, the initial applied load was approximately 1500 N. The applied normal force dropped by approximately 400 to 450 N over the duration of the test. The mechanisms behind this decrease in normal force are fabric nesting and tow compaction. The fabric tows adjust their position as the adjacent layers of fabric nest, tow undulation decreases and fibers compact due to the combination of heat and pressure. Any one or more of these mechanisms causes a slight change in the displacement necessary to maintain the desired normal force.

Due to the drop in normal force, only the static coefficient of friction, which is the value obtained at the first instant of fabric movement, can be reliably quantified. Understanding the dynamic coefficient of friction may lead to a model that more accurately represents the frictional relationship by encompassing the behavior over the entire duration of the thermostamping process. To gain the ability to determine the dynamic coefficient of friction, a force- or pressure- controlled application mechanism is being constructed. The force-controlled mechanism consists of a pneumatic air-spring actuator and a closed-loop control algorithm to continuously monitor and regulate the magnitude of force applied to the fabric surface throughout the duration of the test.

Further considerations in the development of test criteria involve investigating the effects of tow orientation on the friction coefficient. During the thermostamping process, as the punch draws the fabric into the die, the tows rotate to assume the shape of the mating members due to the restrictions placed by the binder ring. This mechanism is referred to as trellis deformation and is shown in Fig. 8.

For the stamping of a hemisphere with a plain-weave fabric (as shown in Fig. 8) the tows are initially oriented 90° from one another, and this angle decreases as the part is stamped. The significance of the effect of tow orientation will be investigated for possible incorporation into the friction subroutine of the finite-element analysis of woven-fabric composite forming behavior.

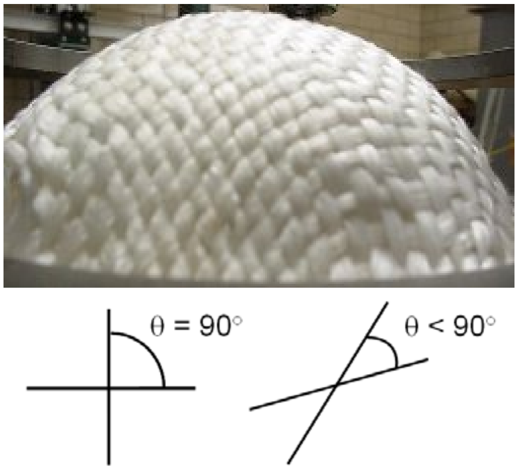


Figure 8. Trellis deformation of a stamped hemisphere.

Additional considerations for the 3rd-generation friction-testing apparatus include the development of a stand-alone test machine. The limiting factor for the current mechanism that withdraws the fabric from between the pressure plates is its dependence on the Instron testing machine. In addition, integrating all fabric movement into one test apparatus will minimize travel time from the oven, therefore reducing any cooling effects as the fabric is transferred. Fig. 9 shows a schematic of the complete proposed 3rd-generation friction-testing apparatus.

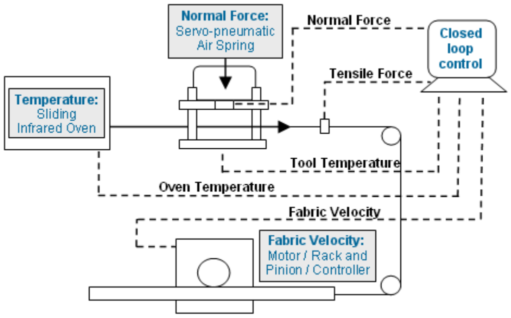


Figure 9. Schematic representation of the 3rd generation friction test apparatus.

Conclusions

Yarn and fiber parameters were investigated and their ability to model the compaction behavior of commingled fibers has been demonstrated by their influence on the resulting shear load-deformation curve. A new friction-test apparatus is under development with a load-control method to apply the normal force to the surface of the fabric, allowing the dynamic coefficient of friction to be quantified. The new design will overcome past limitations identified by previous research and enhance characterization of tool-fabric and fabric-fabric friction coefficients. The analysis of the friction interface will also be extended to the effects of tow orientation as well as to the analysis of the fabrics involved in an international benchmark study. These research tasks are enhancing the fundamental understanding of the mechanical behavior of the commingled fiberglass/ polypropylene woven fabrics and the development of a design tool linking the process-induced properties to the modeling of the in-service performance of thermoplastic composites. To validate and further demonstrate the capabilities of the integrated structure-process-performance design tool, the model will be used to identify critical process and material parameters for one particular performance model – damage tolerance.

Acknowledgements

The authors would like to thank the NSF Division of Design, Manufacture, and Industrial Innovation (DMI #0522923) and Ford Motor Company (Dr. Patrick Blanchard) for their support of this research. The letter of support from General Motors for the grant proposal is also appreciated. The contributions of Dr. Lu Liu, UMass-Lowell graduate and post doc, and MSME candidate Lisa Gamache are appreciated.

References

1. A.E. Long, C.D. Rudd, M. Blagdon, and P. Smith, "Characterizing the processing and performance of aligned reinforcements during perform manufacture," *Composites Part A,* vol. 27A, pp. 247-53, 1996.

2. L. Liu, J. Chen, X. Li, and J.A. Sherwood, "A two dimension macro-mechanics shear model of woven fabrics," *Composite Part A*, vol. 36, pp. 105-114, 2005.

3. L. Liu, J. Chen, J. Gorczyca, and J. Sherwood, "Modeling of friction and shear in thermostamping of composites – part II," *Journal of Composite Materials*, vol. 38, pp. 1931-1947, 2004.

4. L. Liu, J. Chen, and J. Sherwood, "Analytical model of shear of 4-harness satin weave fabrics," American Institute of Physics Proceedings 712, 8th NUMIFORM Technical Conference, June 13-17, Columbus, OH, 2004.

5. A. Bulusu, Modeling of Architecture and Deformation of Dry Woven Fabrics during Shear, MS Thesis, Department of Mechanical Engineering, University of Massachusetts Lowell, Lowell, MA, 2001.

6. I.M. Hutchings, Tribology: Friction and Wear of Engineering Materials, CRC Press, Ann Arbor, MI, 2002.

7. J. Gorczyca, A Study of the Frictional Behavior of a Plain-Weave Fabric during the Thermostamping Process, Doctoral Dissertation, Department of Mechanical Engineering, University of Massachusetts Lowell, Lowell, MA, 2004.

8. J. Gorczyca, J. Sherwood, L. Liu, L. and J. Chen, "Modeling of friction and shear in thermostamping of composites – part I," *Journal of Composite Materials*, vol. 38, pp. 1911-1929. 2004.

9. S. Chow, Frictional Interaction between Blank Holder and Fabric in Stamping of Woven Thermoplastic Composites, MS Thesis, Department of Mechanical Engineering, University of Massachusetts Lowell; Lowell, MA, 2002.