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Investigation of Shear Characterization of a UHMWPE Unidirectional Cross-ply for Finite Element Simulation of Composite Processing

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Abstract. In-plane shearing is the dominant mode of deformation in many composite forming processes, including thermoforming. The shear-frame, or picture-frame, test is a widely accepted method to characterize the shear behavior of a material system to find the properties to use in forming simulations, and this test has been shown to be applicable for providing shear stiffness as a function of the state of shear for a variety of woven-fabrics based material systems. The current research explores the use of shear-frame testing of a non-woven material system made of Ultra High Molecular Weight Polyethylene (UHMWPE), specifically DSM Dyneema® HB210 unidirectional fiber cross-ply. The material system was characterized at an elevated temperature for processing applications. The effects of sample size and sample geometry were investigated. The load contribution from the sample arms is of particular interest for these types of materials, so an investigation of appropriate gage area and normalization methods is performed. Finite element simulations of the shear-frame test are completed to validate the characterization methodology.

INTRODUCTION

Thermoforming is a cost-effective, high-volume production process used for the manufacture of complex shaped thermoplastic composite parts. Thermoforming considered in this effort is a two-step process, as depicted Figure 1a. In the first step, multiple composite sheets (i.e., a blank) are punch formed, between a tool and a mold, at elevated temperature into a loosely assembled shape call a preform. In a secondary step, the preform is consolidated under pressure and elevated temperature in a process that bonds the loosely assembled sheets together, forming a complex-shaped laminated structural component.

The quality of the finished component is generally determined by the end state of the laminate structure. To ensure optimal structural performance, it is desirable that the individual sheets of composite remain flat and retain continuity of their directional orientations during the preforming process. Some typical defects that can degrade performance in thermoformed laminated composites are illustrated in Figure 1b.

The preforming process involves a variety of complex physical phenomena (e.g., in-plane shear deformation, frictional sliding, etc.). These phenomena can be modeled with finite element methods to help guide critical preforming parameters as well as the selection of composite materials and ply orientations to optimize component performance at reduced development time and cost. As shear is the primary mode of deformation during the preform step, characterizing this property in an accurate and reliable manner is critical. In this paper we explore some of the technical challenges in characterizing a UHMWPE unidirectional fiber/matrix cross-ply, DSM Dyneema® HB210. Shear characterization is performed with a shear-frame, or picture-frame, setup. Sample size and configuration, as well as normalization methods are investigated. Finite element analyses are performed using the explicit solver in

LS-DYNA to validate the material characterization results and methodology. This research fits into a larger objective of simulation the two-step thermoforming process.

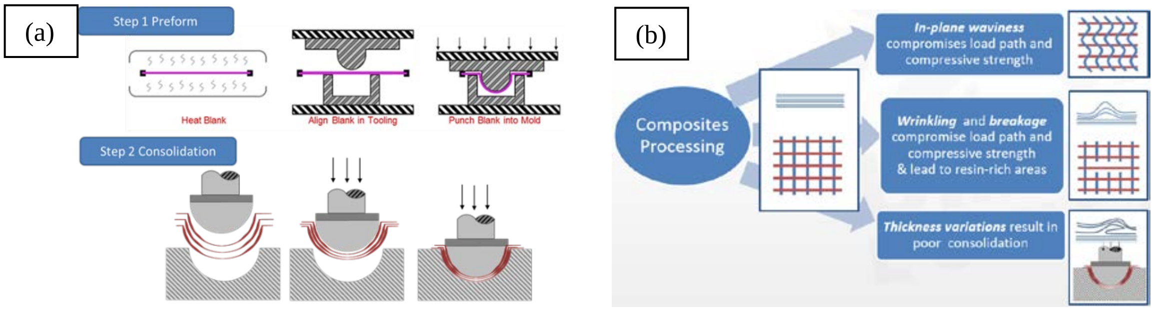

FIGURE 1. Composite thermoforming (a) two-step process and (b) the types of defects that occur.

SHEAR-FRAME EXPERIMENTAL CHARACTERIZATION

Shear behavior is commonly characterized with the shear, or picture, frame test. The contribution of the arm region to the overall load directly impacts how the shear behavior should be analyzed for comparison and modeling. Two extreme scenarios exist: (1) the arm region does not contribute to the load, and the centralgage area is only considered in the analysis or (2) the arm region contributes equally, and the entire specimen area is used for analysis. The third scenario is that the arm region partially contributes, making the analysis much more complicated in determining that partial contribution. In a prior bench-marking study various research groups removed cross-yarns from the arms of woven fabrics for shear-frame testing to remove the arm contribution to the shear load [1]. These cross-yarns were expected to contribute to the overall load, however as they were unbounded on the sides the contribution would not be equal to that of the gage area. In that research, good agreement was made when the central gage area was used for analysis.

Dangora et al. [2] applied the same thought process of removing the arm contribution to a unidirectional cross-ply laminate, DSM Dyneema® HB80. The cross-fibers and resin were removed from the arm area to isolate the shear to the central gage area of the specimen. Good agreement was found when the results were used in finite element modeling of various specimen configurations.

However, removal of cross-material from the arm region is not practical for all materials. Specifically, some unidirectional cross-plies have reinforcement that is not easily removed or resins that cannot be dissolved without damaging the reinforcement. Considering the nature of unidirectional cross-ply systems and how they differ from dry woven systems, the resin will dominate the shear behavior. Likewise, friction from cross-overs and the locking angle do not play a large role because fibers are joined by resin only. This research is aimed to investigate the feasibility of assuming equal load contribution from the arm area. Two methods are used to explore this assumption: varying the sample size and removing the arm contribution.

Sample Size Variations

The material considered in this research is DSM Dyneema® HB210, a thermoplastic cross ply containing four highly directional layers oriented in a $(0/90)_2$ configuration. Each ply is comprised of ultrahigh molecular weight polyethylene (UHMWPE) unidirectional fibers with a polyurethane resin. Three different shear-frame sample sizes shown in TABLE 1 were tested, with varying gage areas that lead to varying proportion of arm area to total area. The samples are shown in Figure 2. The shear tests were performed at 120°C using infrared heating. Three samples were tested for each configuration and Figures 3 show the start and end of all the tests.

TABLE 1. Size Configurations for Shear-Frame Testing

Sample	Gage Side Length	Arm Area / Total Area
A	125 mm	0.6
B	100 mm	0.7
C	75 mm	0.8

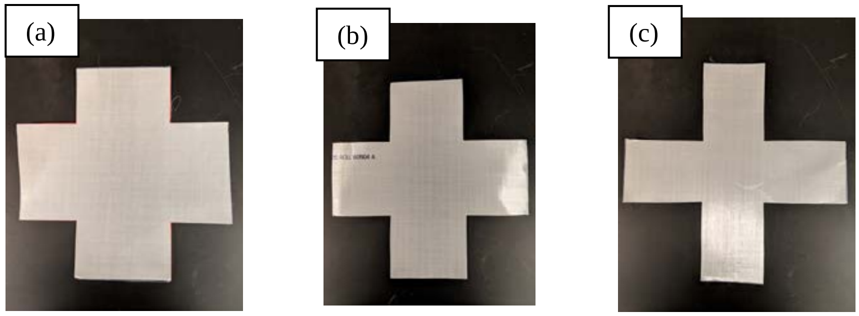

FIGURE 2. Shear test sample (a) 125-mm, (b) 100-mm and (c) 75-mm gage side length with 216-mm total sample width.

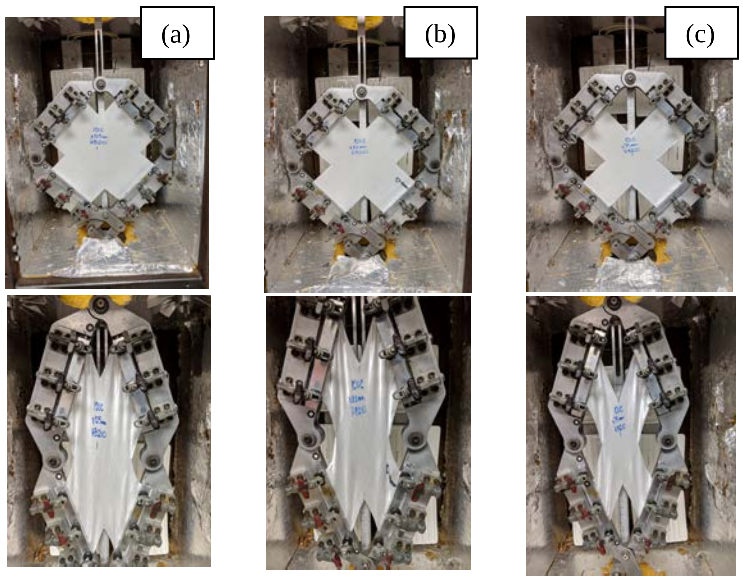

FIGURE 3. Shear frame test at 120°C start and end for (a)125-mm gage area, (b) 100-mm gage area and (c) 75-mm gage area.

Arm Contribution Removal

A comparison of a full-area analysis and a gage-area-only analysis was accomplished by testing a sample with the cross-arm material removed, thereby removing the contribution of the arm region to the total load. The method employed by Dangora et al. [2]on Dyneema HB80 material was used. Acetone was applied to the arm regions to dissolve the PUR and the cross fibers were removed with a fine-toothed comb (Fig. 4a). Three samples were tested in shear at 120°C (Fig. 4b-c).

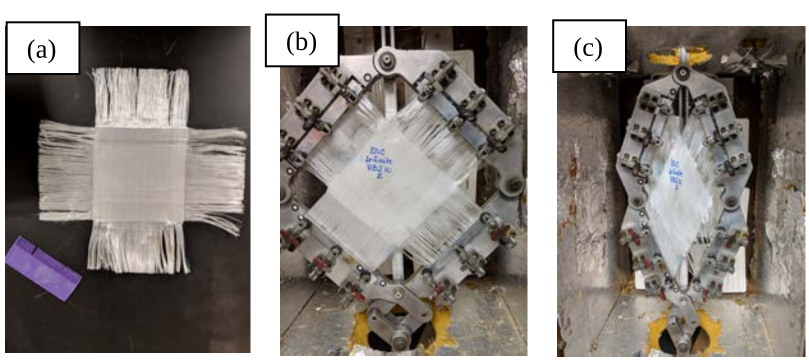

FIGURE 4. 125-mm gage area sample (a) removal of cross-arm material and (b-c) shear testing.

RESULTS AND DISCUSSION

Crosshead displacement and force were recorded in the picture frame tests with the Intron Series IX software. The formulas used to calculate the shear strain and shear stress are typical for picture frame analyses [3-6]. The global shear angle, γ, of the sample is geometrically related to the length of the frame, L_F, and the crosshead displacement, δ through Equation 1.

$$\gamma = \frac{\pi}{2} - 2\cos^{-1}\left[\frac{1}{\sqrt{2}} - \frac{\delta}{2L_F}\right] \tag{1}$$

The shear force, F_{Sh}, on the fabric is also a function of the global shear angle and the crosshead force, F, with Equation 2.

$$F_{sh} = \frac{F}{2\cos\left(\frac{\pi}{4} - \frac{\gamma}{2}\right)} \tag{2}$$

Peng, et al. [1] used a method of normalization for cruciform sample testing based on energy conservation through work done per volume. Using an assumption of zero contribution of load from the arms and uniform shear deformation in the gage area, the shear force can be normalized over the gage area with side length L_f, while also taking the frame length into account. Combining these in to a single expression yields Equation 3 [6].

$$F_{shnorm\_gage} = \frac{L_F}{L_f^2}\frac{F}{2\cos\left(\frac{\pi}{4} - \frac{\gamma}{2}\right)} \tag{3}$$

On the other hand, if the same load contribution is made by the arm parts as the gage area the load would be analyzed using the entire area of the sample, including arms [1]:

$$F_{shnorm\_entire} = \frac{L_F}{\left(L_f^2 + 2(L_F - L_f)L_f\right)}\frac{F}{2\cos\left(\frac{\pi}{4} - \frac{\gamma}{2}\right)} \tag{4}$$

Both Equations 3 and 4 will be used to evaluate the two different scenerios for comparison.

Three samples of each size were tested in shear at a processing temperature of 120°C. As expected, the measured load decreased with the area of the sample (Fig.5). The sample with the cross-arm material removed exhibits higher variability than the full-arm samples. Based on challenges with mounting the free fibers into the frame, a spread in the data was expected. The error bars denote one standard deviation

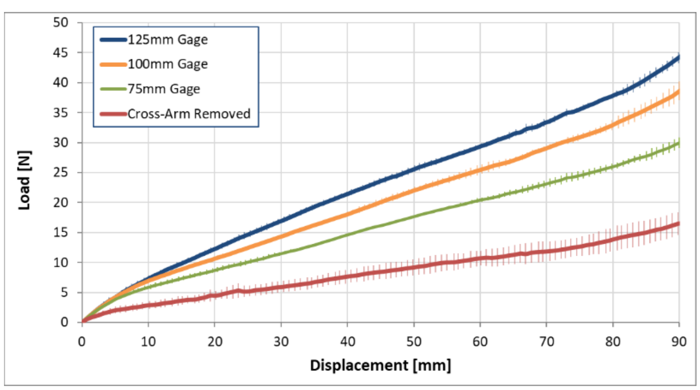

FIGURE 5. Load vs. crosshead displacement results for shear frame testing.

Two normalization methods were used for the full-arm samples: (1) Equation 3 that assumes the gage area only contributes and (2) Equation 4 that assumes the arms contribute equally. Figure 6a shows that normalizing with the gage area reverses the order of the results, with the smallest gage area having the highest normalized force. However, when the result are normalized using the full sample area the curves come together in Figure 6b, with the samples with varying sizes converging to a single curve as expected if the arms are contributing equally. The samples with the full arms also come very close to matching the sample with the cross-arm material removed. One reason for a lower load for the sample with the material removed is that there was little control over the amount of PUR that was dissolved by the acetone, which would lead to a some of the resin being removed in the gage area. The result would be lower force on those samples. Also, large variations in the three samples testing mean that more testing is required to validate these results.

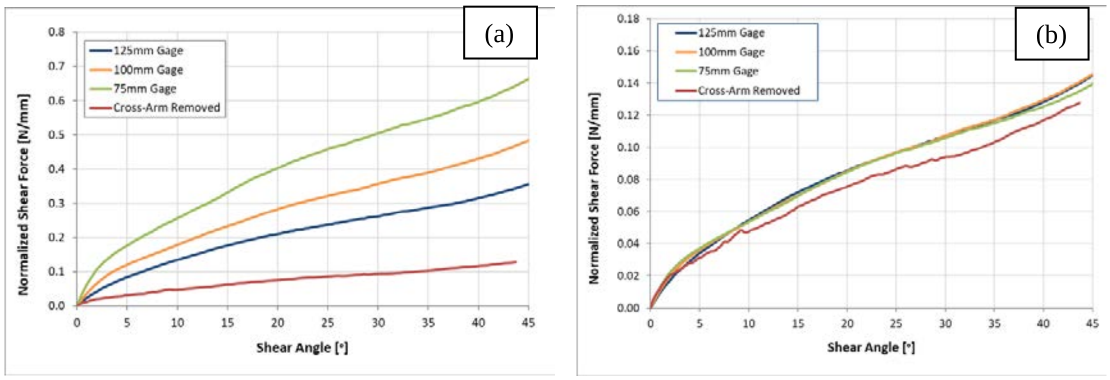

FIGURE 6. Normalized shear force (a) assuming no arm contribution and (b) assuming equal arm contribution.

FINITE ELEMENT MODELING

The shear frame experiments were modeled with a mesoscopic modeling method with a user-defined material model in LS-DYNA. Beam elements represent the tensile behavior and in-plane orientation of the material while shell elements carry the shear load. Figures 7a and 7b show the models for the full arm and cross-arm material removed. The shear curve from the full-arm 125-mm gage area normalized using the full area was used for the shear behavior of the shell elements. The tensile modulus found during previous testing was used.

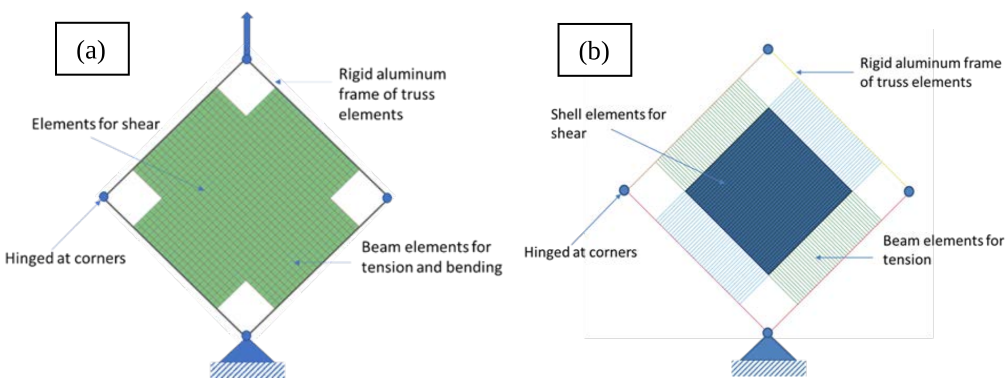

FIGURE 7. Finite element moodel of (a) full-arm speciments and (b) cross-arm material removed.

Four configurations (three different sample sizes and cross-arm material removed) were modeled using the data from the full-arm 125-mm specimen. Figure 8 shows good agreement in all four cases, which implies that full-arm tests could be used to characterize this class of unidirectional cross-ply laminates. However, more samples should be tested with the cross-arm material because of the high vatiation in testing data.

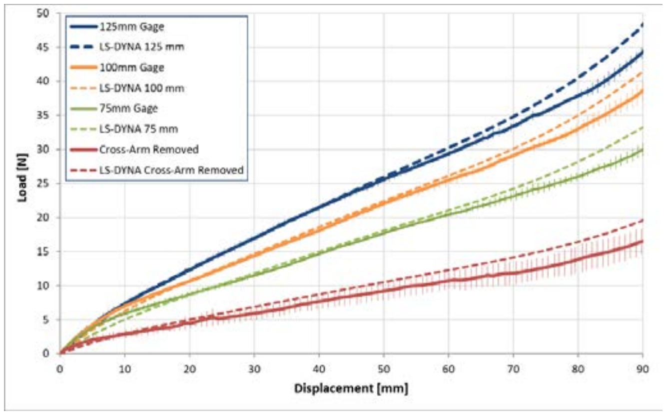

FIGURE 8. Finite element results from four configurations using full-arm data.

CONCLUSION

This paper discussed the shear characterization of a UHMWPE material system for use in process simulation. An investigation of sample size and arm contribution was performed. Shear force curves from three different sample sizes were normalized with the full specimen area and converged to one curve. The result was used as an input into a LS-DYNA finite element model to simulate the shear frame tests with good agreement. Shear frame tests were also performed on samples with the cross-arm material removed to limit the shearing to the central gage area for comparison. Although there was large variation in the test results, the curve was good match to the normalized full-arm specimens. Likewise, the modified sample results were predicted well using full-arm characterization data in the simulation. These results imply that characterizing shear with full-arm specimens is acceptable for input into process simulation. However, more testing needs to be done to confirm given the limited number of experimental tests that were performed. Future testing will be performed with digital image correlation and an additional material. Thank you to Jan Stolk from DSM for providing Dyneema HB311 material system for characterization.

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