Modeling of a Cross-Ply Thermoplastic for Thermoforming of Composite Sheets in LS-DYNA®

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Abstract

Thermoforming is a very attractive process for the cost-effective high-volume production of high-performance composite parts. The process starts with an open-punch tool to produce a set of preforms. The preforms are then consolidated into a part using matched-tooling high-pressure compression molding. However, this process is prone to the formation of defects such as wrinkling of the plies as they conform to the compound-curvature geometries of the tool and poor consolidation of the set of preforms due to non-uniform thickness of the preforms. Thus, the processing options must be well understood, so the composite manufacturing process can be designed to mitigate wrinkling and to achieve full consolidation and thereby produce high-quality parts. The finite element method is well suited to give insight into how changes in the processing parameters such as binder pressure, temperature, tool speed, material properties and ply/ply and tool/ply frictions can impact part quality. A robust finite model can predict if and where wrinkles may precipitate and the degree of consolidation for a given set of process settings. Such a robust model requires a complete characterization of the mechanical behaviors of the material systems. The current research uses the temperature-dependent material properties of Dyneema® HB80, a cross-ply lamina sheet, and DuPont™ Tensylon™ HSBD 30A, a bidirectional laminate tape, both known for their excellent ability to dissipate energy during impact, as inputs to a user-defined material model for LS-DYNA simulations. A hybrid discrete mesoscopic approach is employed to simulate the tensile and shear frame experimental characterization tests. Finite element simulations of the characterization experiments are compared to experimental results of the same to validate that the user-defined material model can replicate the experiments from which the material constants were derived. The current work shows excellent agreement between the model and the results from tensile and shear-frame experiments. Future work will incorporate material bending and ply/ply and tool/ply frictions. The ultimate goal is for the procedures that are used for conducting the material characterizations and for the process simulations that are developed in this research to be integrated into a Virtual Design Framework, where the part will be designed, manufactured and "tested" for field performance using a set of well-connected CAD/CAE tools, thereby minimizing the dependence on the design-build-test methodology.

Introduction

The process of thermoforming fabric-reinforced composites is capable of producing lightweight, quality parts relatively fast with reasonably low processing costs [1]. The thermoforming process uses heat and pressure to transform flat sheet laminates into a desired three-dimensional shape [2]. However, the lack of knowing if and where defects, such as out-of-plane wrinkles, can develop during the forming process can be a limiting factor in the widespread use of thermoforming for making composite parts. A manufacturing defect such as wrinkling can result in compromised load paths and stress concentrations that can lead to catastrophic and premature failures [3].

The primary deformation mechanism of the reinforcement material is in-plane shear. The areal coverage of the material decreases when sheared, but the fibers within the ply layers of the stack maintain the same volume; therefore, the laminate thickness increases with local shear [4]. Thus, varying degrees of shear of the material as it deforms to conform to the geometry of the mold results in thickness variations across the surface of the part that can result in a non-uniform pressure distribution between matched die tooling, allowing weakened, resin-rich areas to form [5] as well as incomplete consolidation of the ply stack (Fig. 1).

Because wrinkling of the composite reinforcement, incomplete consolidation and resin-rich areas can result in a compromised structural performance, it is important that the effects of the various manufacturing processing parameters be well understood so the overall manufacturing process can be designed to mitigate the formation of such defects. As a result, the processing parameters will be driven by the forming limits of the material and the relative complexity of the part geometry. Unfortunately, the processing conditions that will lead to consolidation problems are not always known before the development phase. Consequently, correction of adverse product features is often accomplished with a design-build-test regimen, which can be costly, wasteful, and time consuming. A simulation tool that can perform the design-build-test activity in a virtual setting would provide a cost-effective and time-efficient solution to product development and process design, and ultimately high confidence in the use of composites.

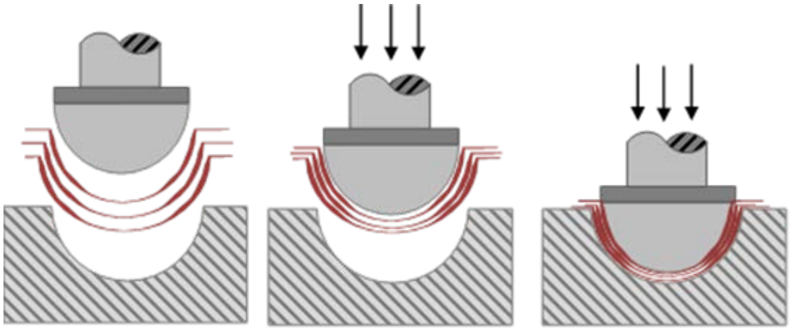

FIGURE 1. Thickness variations in preforms lead to pressure differences during consolidation phase.

“Fishnet” algorithms are very popular to predict the deformation of the fiber blank as it conforms to the tool geometry. This “fishnet” approach is fast and numerically efficient, but it fails to account for the mechanical behavior of the fabric or the effect of the boundary conditions such as binder pressure. As a result, process-induced defects such as wrinkling and thinned and/or thickened spots will not be captured in the simulation. Therefore, a simulation method that includes material behavior is necessary to predict the locations and magnitudes of defects that may develop during manufacture.

Using a discrete mesoscopic finite element model, information regarding fiber orientations, stresses and strains can be mapped over the preform surface and monitored throughout the forming process [3]. With a complete set of material properties for describing the material behavior, the simulation tool will be able to identify potential defects (e.g., in-plane waves, out-of-plane wrinkles, fabric folding, fiber tearing and thickness changes) that arise during manufacture and compromise the part performance. For many applications, multiple layers of one or more types of fabrics are used and filler layers may need to be implemented to add material to areas surrounding the thickened regions. Thus, predicting the regions that require filler plies is critical if a thermoforming process simulation is going to assist in the design of a charge of plies and processing conditions that will result in a uniform thickness part. Results of the finite element analysis (FEA) can therefore be used to guide the selection of processing parameters (e.g., tool velocity, forming temperature, binder pressure, material selection, ply geometry, and binder size) such that the resulting preform satisfies the design constraints (e.g., fiber orientations, uniform thickness and low seam density).

The scope of the current research is to demonstrate capabilities of a discrete mesoscopic finite element model that considers the mechanical behaviors of the material during a forming simulation. Various ultrahigh molecular weight polyethylene material systems are being investigated through a procedure of material characterization, finite element modeling of the experimental characterization to validate and update the material model and implementation of the material model into a full preform to consolidation finite element process simulation. This paper presents the LS-DYNA simulation of tensile and shear frame material characterization experiments performed on two UHMWPE material systems.

Modeling Approach

The specific (UHMWPE) materials considered in this research are Dyneema® HB80 and DuPont™ Tensylon™ HSBD 30A. Dyneema HB80 is a thermoplastic cross-ply containing four unidirectional layers oriented in a $(0/90)_2$ fiber configuration with each ply comprised of UHMWPE fibers and a thermoplastic polyurethane (TPU) based matrix. Tensylon™ 30A is a bidirectional laminate tape system of two 0/90 layers of highly directional UHMWPE solid extruded tape. Although the simulation methodology is evaluated for the two material systems in this paper, the methodology is applicable to a wide range of materials undergoing a similar manufacturing process. Tensile and shear frame testing was performed at elevated temperatures to inform the user-defined material subroutine [7].

The modeling performed for this research was accomplished at the mesoscopic scale using a discrete approach developed by Jauffrès et al. [3] employing a hypoelastic element description with an explicit formulation. Beam elements incorporate the tensile and flexural properties of the fibers, and the shell elements define the shear response of the sheet. For example, a cross-ply is discretized into a mixed-mesh grid where each unit cell consists of four beam elements and one shell element (Fig. 2).

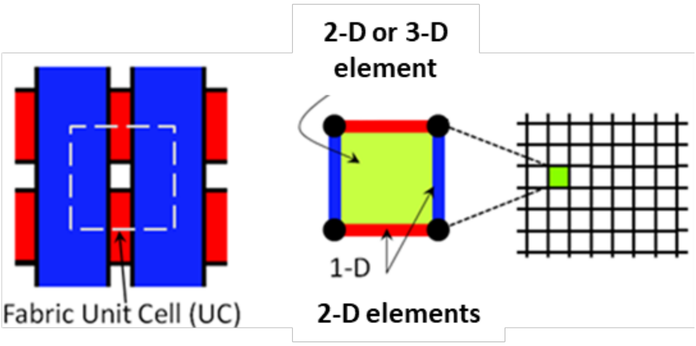

FIGURE 2. Unit cell configuration for mesoscopic laminate material model.

The shell element has no tensile/compression properties and only possesses the in-plane shear stiffness that varies with the degree of shear at that point in the ply. The two horizontal beam elements are defined using properties of the 0° direction fibers/tows, and the two vertical beam elements are defined using properties of the 90° direction. A single node is used to connect the intersecting beam elements at each of the shell corners. This joining of the beams assumes a “no slip” condition between 0° and 90° layers and has been demonstrated through the correlation of the model with experimental data to be an acceptable assumption for the materials being investigated. This modeling technique has been successfully applied to a variety of textile architectures including woven, unidirectional, and non-crimp fabrics [3].

For this research, LS-DYNA is being used to replicate analyses that were previously completed in Abaqus. LS-DYNA offers capabilities for analyzing large, nonlinear, quasi-static problems, such as deep-draw thermoforming, and shows promise in the ability to simulate laminate thickness changes that occur during preforming and play a role in consolidation. User-defined material subroutines are linked with LS-DYNA to implement the laminate shear, tensile and bending behaviors. The accuracy of the simulation depends on the quality of the fabric bending, tension, and shear material constants which are derived from material characterization tests.

Tensile Characterization

Tensile testing is typically the first step in the material characterization process. Gripping method, gauge length, elevated temperatures are among the challenges that are encountered with each new material system. Figure 3 shows the specific test setup used for the tensile testing of the UHMWPE material systems, with modifications made as necessary for the particular system under consideration. A range of temperatures were explored during each material characterization so that exploration of temperature as a processing parameter can be performed in the simulation. The tensile results as a function of temperature for the Dyneema HB80 and Tensylon 30A systems are given for the initial elastic regions of the tests that are of interest for input into the finite element material model (Fig. 4) [4].

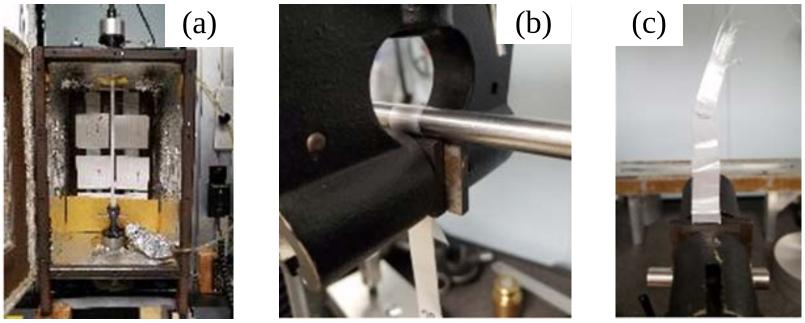

FIGURE 3. Tensile testing setup in (a) infrared oven with (b) modified pin-gripping system that leads to (c) failure in gauge section.

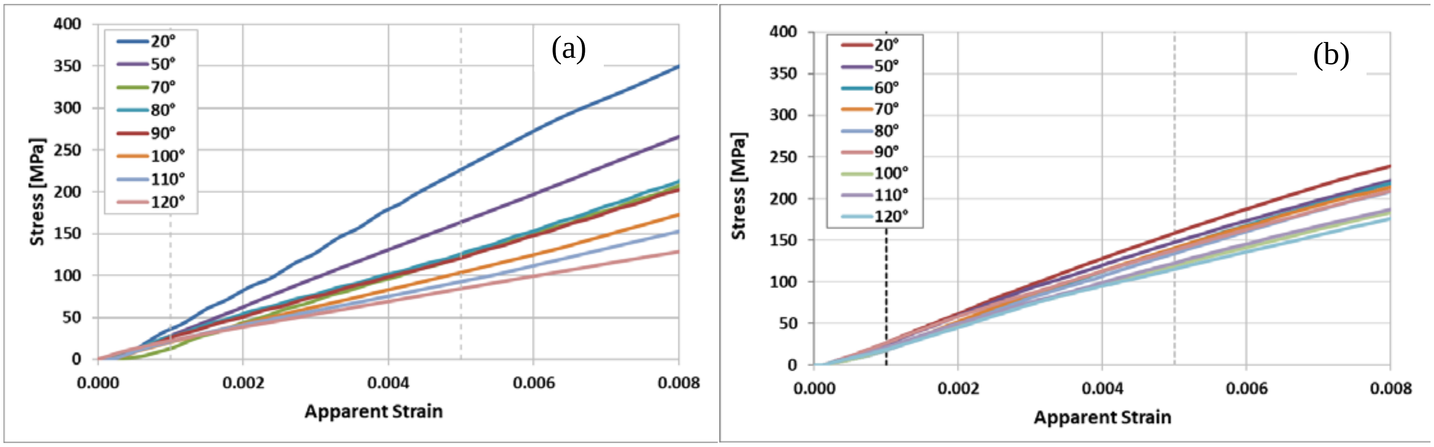

FIGURE 4. Temperature-dependent tension testing results for (a) Dyneema HB80 [4] and (b) Tensylon 30A.

For the material model to be considered credible, it must demonstrate that it can replicate each of the material characterization tests from which the material parameters were derived. The LS-DYNA simulations of the tension tests were performed on both materials with properties at 90°C using elastic tensile properties in the user material subroutine. Comparisons of the experimental results to the simulation results show excellent correlation (Fig. 5).

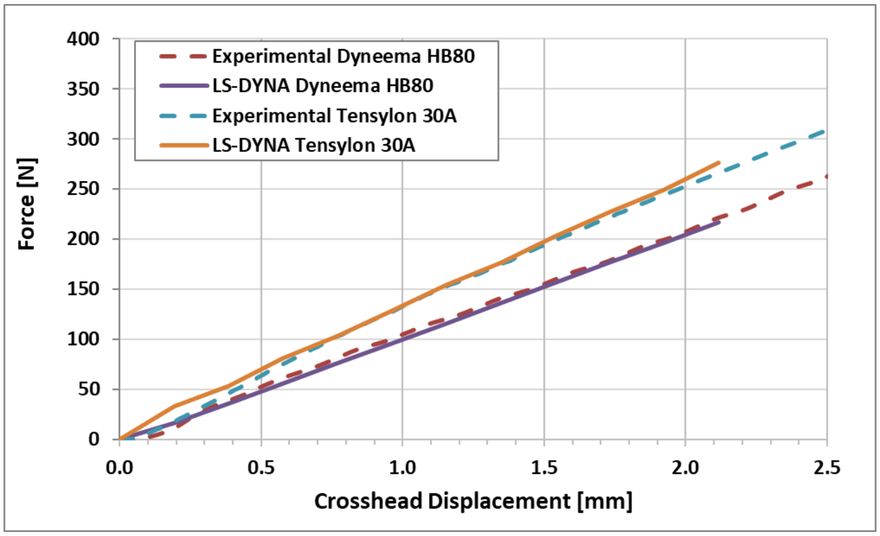

FIGURE 5. LS-DYNA simulation validation of material model for experimental tension tests of Dyneema HB80 and Tensylon 30A at 90°C.

Shear Characterization

Shear characterization was performed on a trellis shear frame. This test was conducted inside an infrared oven to perform the tests over a range of elevated temperatures (Fig. 6). Dangora et al. found that adding slits to the arms of cross-ply materials is necessary to develop a state of pure shear in the central test area of the specimen [5]. They tested the Dyneema HB80 material in shear with no slits, 25-mm slits, 13-mm slits, 6-mm slits and 'infinite' slits (with all material removed from between each fiber) with the researchers showing that the 'infinite' slit data best captured the shear properties to be used in a finite element analysis (Figs. 7 and 8).

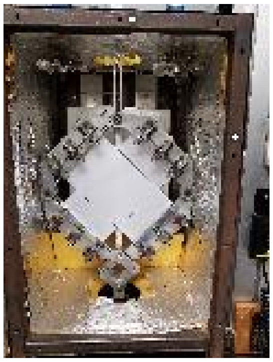

FIGURE 6. Trellis shear frame elevated temperature test setup.

FIGURE 7. Specimen preparation of Dyneema HB80 for 'infinite' slit case [5].

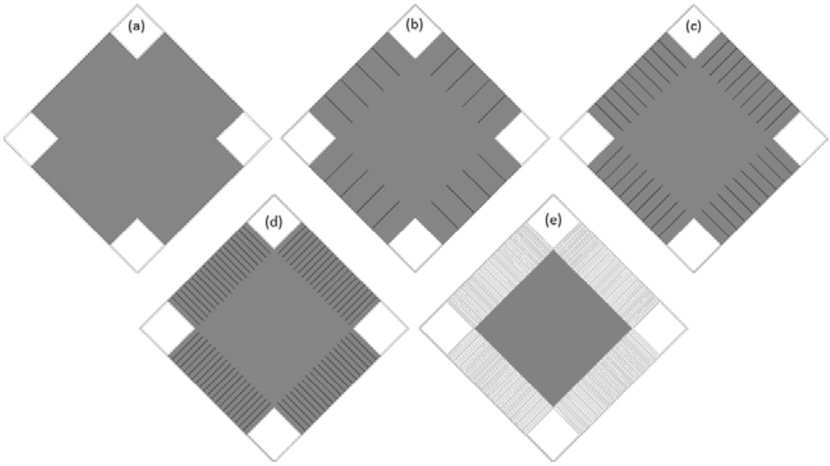

FIGURE 8. Sample variations for FEA specimens with (a) no slits, (b) 25-mm slits, (c) 13-mm slits, (d) 6-mm slits and (e) 'infinite' slits [5].

Shear frame models were built in LS-DYNA using the tension and ‘infinite’ slits shear characterization properties determined for Dyneema HB80 at 90°C. The user material model incoporated the properties as given in Table I. For the LS-DYNA model of the shear-frame test, general shell elements (ELFORM 6) provided the in-plane shear stiffness while beam elements (ELFORM 2) provided the tensile properties in this iteration of the material model. The models examined were for the ‘infinite’ slit case that uses single beams to represent the arms of the specimen and the no-slit case that extends the laminate to the edge of the shear frame (Fig. 9).

TABLE I. Summary of Material Constants for Dyneema HB80 at 90°C

Property	**Value**
Tensile Modulus (MPa)	25,160
Shear Stiffness* (MPa)	$50\lvert\gamma\rvert^4 - 112\lvert\gamma\rvert^3 + 90\lvert\gamma\rvert^2 - 30\lvert\gamma\rvert + 4$
Poisson’s Ratio	0.49

*Note that γ is defined as the shear strain of the composite lamina

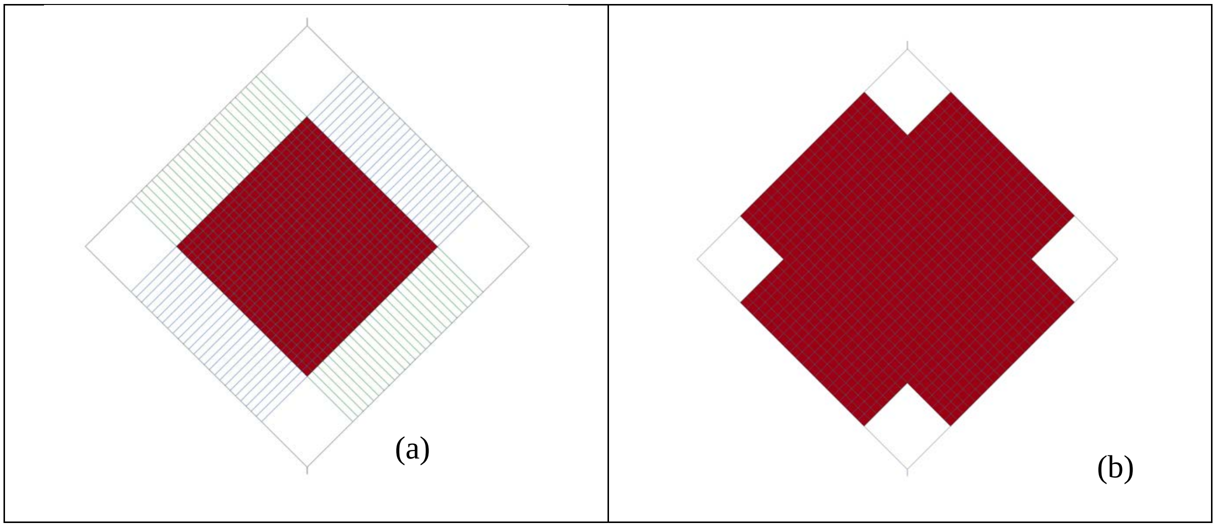

FIGURE 9. LS-DYNA shear frame (a) 'infinite' slit and (b) no slit shear frame models.

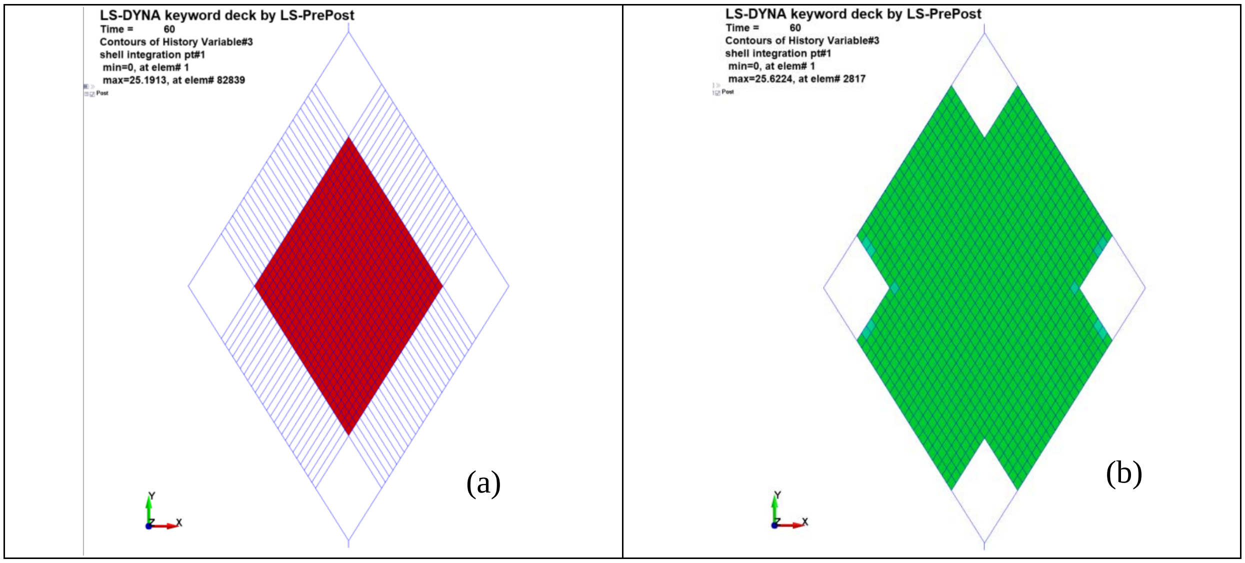

FIGURE 10. Shear frame simulation shear angle results.

The shear angle is uniform across the center of the specimen, but as expected there are slight variations in the arm regions of the specimen without slits in the same fashion as the experimental results (Fig. 10). Load-crosshead displacement data shows excellent agreement between the experiment and simulation for the ‘infinite’ slits scenario (Fig. 11). However, the FE simulation predicted a slightly higher load curve for the no slit case. One cause of discrepancy may be caused edge conditions where the laminate meets the frame. Further investigation into this phenomenon will be conducted with other materials and modeling procedures.

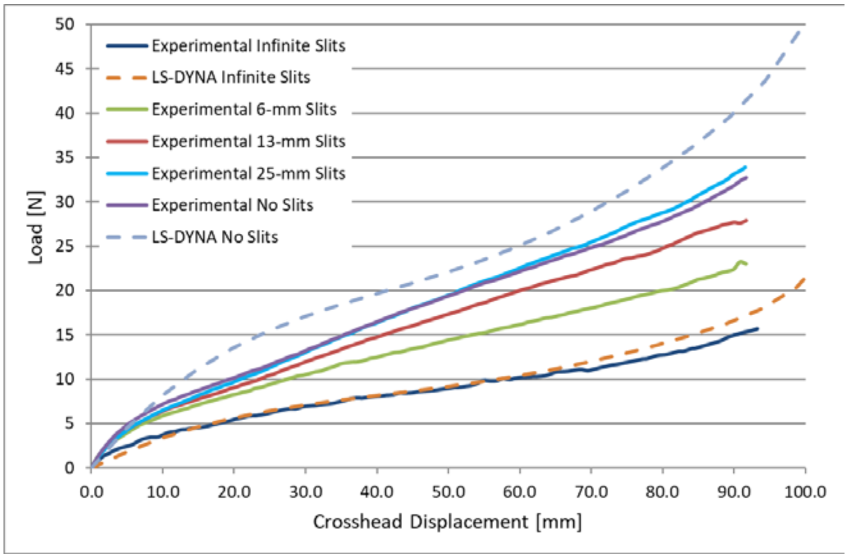

FIGURE 11. LS-DYNA and experimental shear frame results for Dyneema HB80 at 90C.

Conclusions

The laminate user material subroutine linked with LS-DYNA was shown to accurately capture the tensile behavior. Likewise, the model shows promise in representing the shear behavior with attention to model details. Wrinkling in the form of bending behavior of the beams, as well as thickness changes induced by shearing and ply compression are the next properties that are to be incorporated into the material model. Upon validation of the material model through extensive replication of experimental characterization tests, the thermoforming process simulation can be modeled confidently to guide parametric improvements.

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References

1. High Performance Materials – DuPont™ Tensylon™ | DuPont USA 2018 [Available from: http://www.dupont.com/products-and-services/personal-protective-equipment/vehicle-armor/products/dupont-tensylon.html.
2. Gorczyca-Cole JL, Sherwood JA, Chen J. A friction model for thermostamping commingled glass–polypropylene woven fabrics. Composites Part A. 2007;38:393-406.
3. Jauffrès D, Sherwood JA, Morris CD, Chen J. Discrete mesoscopic modeling for the simulation of woven-fabric reinforcement forming. International Journal of Material Forming. 2010;3(2):1205-16.
4. Dangora LM, Mitchell C, White KD, Sherwood JA, Parker JC. Characterization of temperature-dependent tensile and flexural rigidities of a cross-ply thermoplastic lamina with implementation into a forming model. International Journal of Material Forming. 2016:1-10.
5. Dangora LM, Hansen CJ, Mitchell CJ, Sherwood JA, Parker JC. Challenges associated with shear characterization of a cross-ply thermoplastic lamina using picture frame tests. Composites Part A: Applied Science and Manufacturing. 2015;78:181-90.