Using LS-DYNA® to Simulate the Thermoforming of Woven-Fabric Reinforced Composites

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Abstract

Thermoforming of fabrics is a composite manufacturing process that has the potential to yield quality parts with production costs and cycle times comparable to the fabrication of stamped metal parts. Uncertainties in material behavior and processing conditions can result in an overdesigned product with unnecessary increases in weight and cost. As such, there is a widespread interest in having a reliable model to simulate the manufacturing of fiber-reinforced composites to design the thermoforming process that can produce high-quality parts. With the insight provided by a virtual model, the need for an iterative design-build-test regimen could be reduced or even eliminated. To have a credible simulation, the design tool must capture the evolution of changing fiber orientation as the fabric is formed to the mold. A hybrid finite element model using a discrete mesoscopic approach has been implemented in LS-DYNA to simulate the fabric deformation during thermoforming and it can be used to predict when and where defects, such as waviness and tears, are likely to develop; however, it is crucial that the user understand the effects that different modeling options have on the results of the simulation. In the current research, LS-DYNA will be used to simulate the forming a plain-weave (PW) Twintex® fabric made of commingled E-Glass and polypropylene tows. Various modeling options in LS-DYNA were investigated to observe the effect on the final simulation results. The results of this investigation will serve to educate users in applying the appropriate modeling options for such an application.

Introduction

Researchers have demonstrated that thermoforming of pre-pregs and commingled fabrics can be a cost-effective composite manufacturing process with cycle times of merely seconds [1]. The thermoforming process, illustrated in Figure 1, begins with alignment of the fabric in a rigid frame. Typically, multiple ply layers are simultaneously stamped into the mold to achieve the desired part thickness and mechanical properties. The individual plies can be oriented and aligned in the frame to give the desired directional performance needed for the intended function of the composite part. The loaded frame is transported along shuttle rails to an oven where it is heated until the polymer matrix is hot enough to flow with reasonably low viscosity. Because the traditional materials used for this manufacturing process are fabrics with commingled tows or pre-impregnated sheets, there is no need for a resin infusion step. The frame is moved from the oven to the molding area and aligned between a punch and die; binder plates are conventionally used to apply force around the circumference of the part. The application of pressure to the binder plate induces in-plane forces in the fabric that can reduce wrinkling as it is drawn into the die by the punch. A velocity is then prescribed to the punch to force the ply stack into the die mold. The tools (punch, die and binder plate) are often heated to slow the rate at which the polymer matrix cools. The finished piece assumes the geometry of the die and punch and hardens into a solid part after the matrix has cooled.

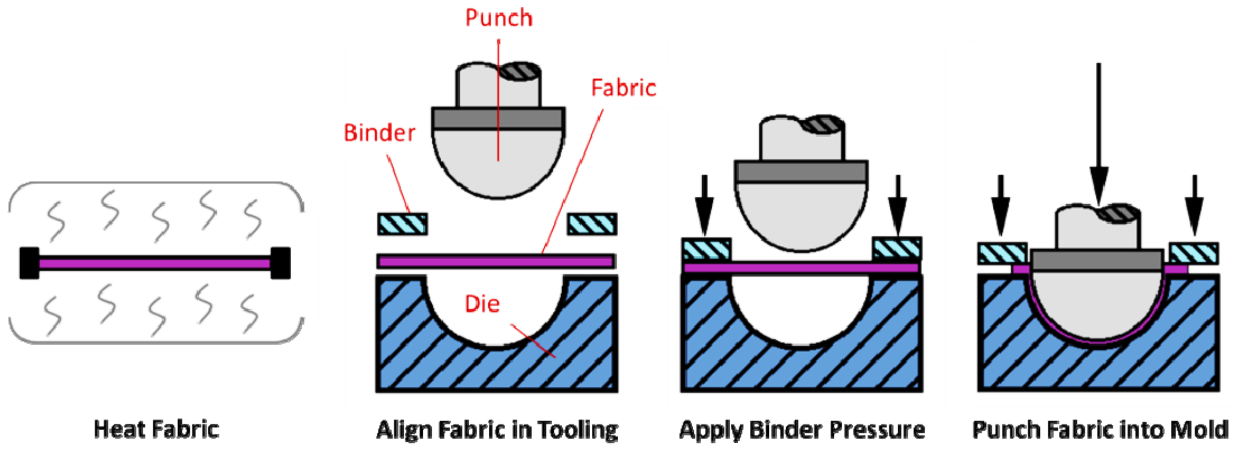


Figure 1. Schematic of thermoforming process

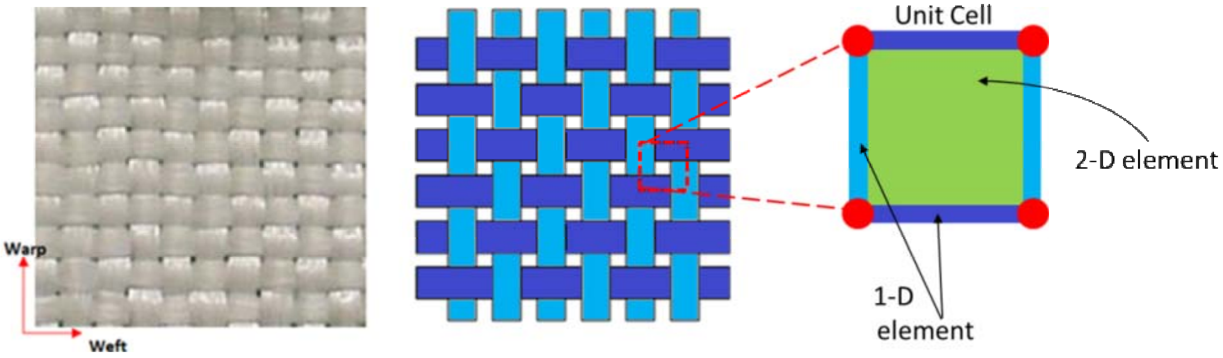
In the current research, LS-DYNA is used to simulate the thermoforming of a plain-weave (PW) Twintex® fabric (Figure 2a) made of commingled E-Glass and polypropylene filaments. The processing parameters, e.g. the use or nonuse of binders, associated with the thermoforming operation can have a significant effect on part quality. LS-DYNA offers the ability to investigate through simulation how choices in the processing parameters can influence part quality. However, before using LS-DYNA for such an investigation, an understanding of the how modeling options influence the simulation results must be available to the modeler. The objective of this paper is to explore some of these modeling options.

Fabric Model and Characterization

Simulation of the forming process can assist in the design of composites by linking the final cured part back to the manufacturing process. A reliable model, requiring a comprehensive understanding of the fabric's mechanical behavior, will help to explore the processing conditions in which components can be formed without defects (e.g., wrinkles or tearing) while maintaining short cycle times and high volume production. In addition, a simulation tool can provide the orientation of the fabric constituents after thermoforming which is of great significance for structural analysis (e.g., stiffness and damage tolerance) of the formed part. The finite element method is very amenable to the development of such a simulation tool for fiber-reinforced composites because it can account for the mechanical behavior of the fabric and the complex boundary conditions experienced during manufacturing.

Fabric Model

A hybrid finite element model using a discrete mesoscopic approach has been implemented in LS-DYNA to simulate the forming of composite parts using a woven fabric (Figure 2b). This approach uses conventional elements found in commercial finite element packages and the direct integration with off the shelf software makes the model appealing to industry. Beam elements represent the tensile properties of the warp and weft tows while shell elements account for the shear properties of the dry fabric. Details of the beam-shell model are given in [2]. This modeling technique captures the evolution of the principal load paths as the tows reorient during the thermoforming process. Figure 2c shows the representative unit cell for modeling the woven fabric. This unit cell is repeated in a regular pattern to generate the fabric mesh.



(a) (b) (c)

Figure 2. (a) Plain-weave Twintex fabric, (b) schematic of warp/weft layout, and (c) unit cell

Material Characterization

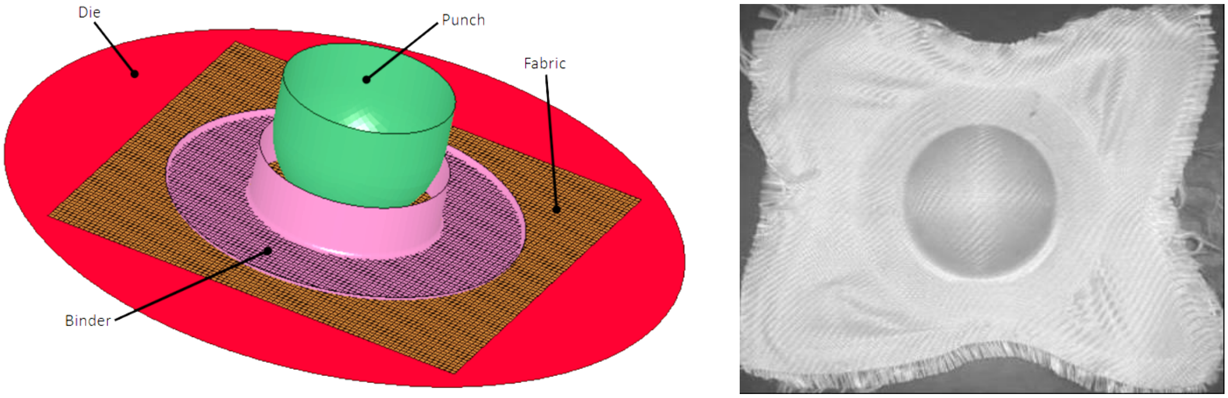
To accurately represent the fabric in the finite element model, the material must be well characterized. For a woven fabric, the two deformation mechanisms at the mesoscopic scale are (1) decrimping (straightening) of the fibers and (2) in-plane shearing of the fabric. The tensile deformation of the yarns is primarily a result of the decrimping. After the yarns have fully extended, then in-plane shearing is the principal mode of deformation during the thermoforming process. This shear deformation results in a change of angle between warp and weft tows and the inter-ply tow rotations allow the fabric to trellis such that it can conform to three-dimensional compound-curvature surfaces. Experimental testing is performed to measure the tensile [3] and shear behaviors of the fabric [4]. It is important to incorporate these measured material properties into the finite element model to generate an accurate forming simulation. Regressions of experimental data are used to conclude empirical models that are then implemented into the user-defined material subroutines to capture the mechanical behavior of the fabric in the finite element solver. Finite element models of the various tests are completed to validate that the fabric behavior can be properly simulated using the finite element method. Additionally, a bias-extension test [5] can be performed experimentally and compared with simulation predictions to confirm that the combined response from shear and tensile forces can be accurately captured by the finite element analysis.

Exploring Contact Damping in LS-DYNA

Once it was verified that the fabric behavior was properly represented in the finite element model, a forming simulation was analyzed using the hemisphere assembly shown in Figure 3a. The forming analysis used the plain-weave material model and a circular binder ring was simulated to apply tension in the yarns during the manufacturing process. The forming simulations, however, were not converging to a solution due to high-frequency waves that propagated through the fabric as it came in contact with the punch. The implementation of contact damping was therefore investigated as a means to resolve the convergence issues. Because such parts can be formed using this material system and tooling (Figure 3b) and if the simulation is to be judged as credible, then the modeling technique should be capable of capturing what physically can be made.

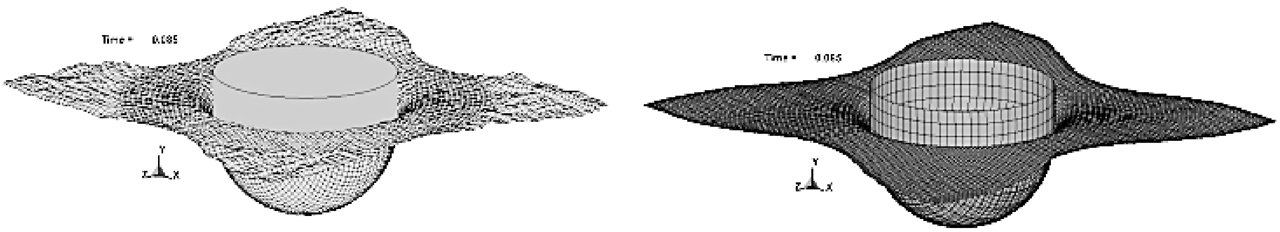
For forming simulations, 20% of critical viscous damping (VDC) is recommended by LSTC [6] to attenuate the high-frequency dynamics. The hemisphere stamping model with no VDC would only reach 85% completion, while the model with a VDC value of 20 ran to 100% completion.

Figure 4 shows a comparison of the two simulations at 85% completion, where the models have VDC values of 0 and 20. In the absence of damping, a simulation may give the false impression that out-of-plane wave defects are developed as a consequence of the fabric behavior when subjected to the forming process.



(a) (b)

Figure 3. (a) Part layup for thermoforming model and (b) formed hemisphere



(a) (b)

Figure 4. Hemispherical stamping with (a) 0% and (b) 20% critical damping

Because this fabric can form a hemisphere without exhibiting the excessive wave displacements as shown in Figure 3b, it is assumed that these out-of-plane wrinkles in the model are a consequence of the dynamic effects inherent to the numerical method and not a physical phenomenon associated with the fabric. Thus, the use of a nonzero value for VDC is justified if it removes a mechanical behavior of the fabric from the model that does not physically exist. For example, the fabric may naturally dampen such oscillations associated with high-frequency dynamics. Thus, the use of damping must be well characterized by comparing to experimental data before it can be used with confidence in the completion of forming simulations.

Models with VDC values of 5%, 10%, 15%, 20% and 25% of critical were analyzed to explore the effect of critical viscous damping on the required punch force. A comparison of the required punch force for various VDC values showed little to no difference from the baseline model (0% damping). The maximum percent difference in the punch force between the baseline model and the six simulations of varying VCD was 8.57% occurring at 42 mm of punch displacement (70% completion) for 15% of critical damping. Shear contour for this model with the maximum difference was compared with the baseline contour and no differences were seen. The comparison indicates that, although there is an 8.57% difference in the punch force, the shear angles in both models are essentially the same. The calculation of the shear angle, which is a measure of part quality, is of greater interest than the accuracy of the punch force data. Thus, the use of VDC to eliminate high frequency dynamics within the model does not compromise the intent of the modeling to capture the final state of fabric deformation which can subsequently be used for structural analyses.

Forming Simulations

For forming simulations that have unrestrained fabric, i.e. no binder, LS-DYNA initially exhibited difficulties converging to a solution due to wave-like effects in the unclamped region of the fabric or “free” fabric areas. An example of such modeling issues is shown in Figure 5 for the forming of a double-dome part without the use of a binder. The “free” fabric hemisphere stamping models experienced the same “wrinkling” issues as the “free” fabric double-dome models. Because this fabric can be formed without a binder, it was speculated that the convergence issues stemmed from inertial effects introduced by the finite element solver.

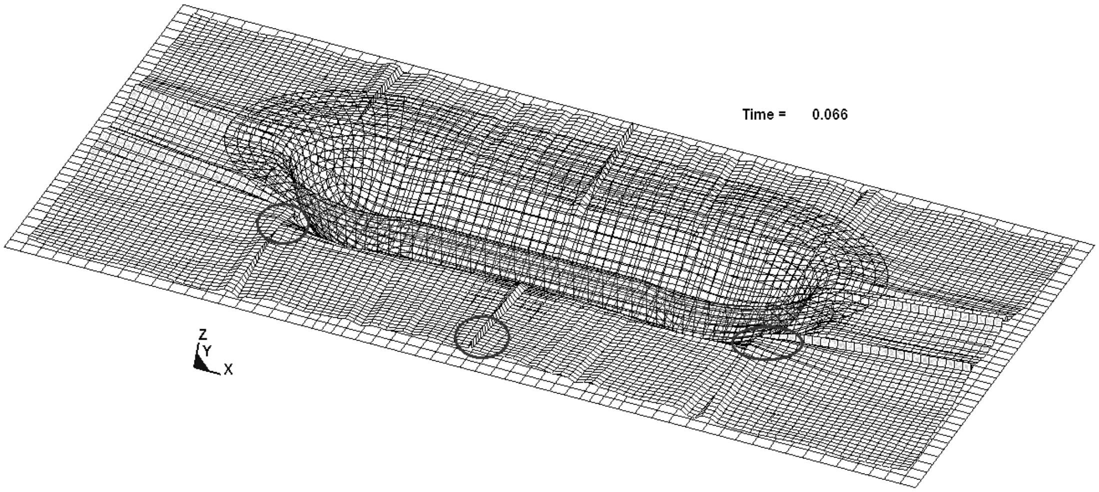


Figure 5. Double-dome stamping simulation of “free” fabric

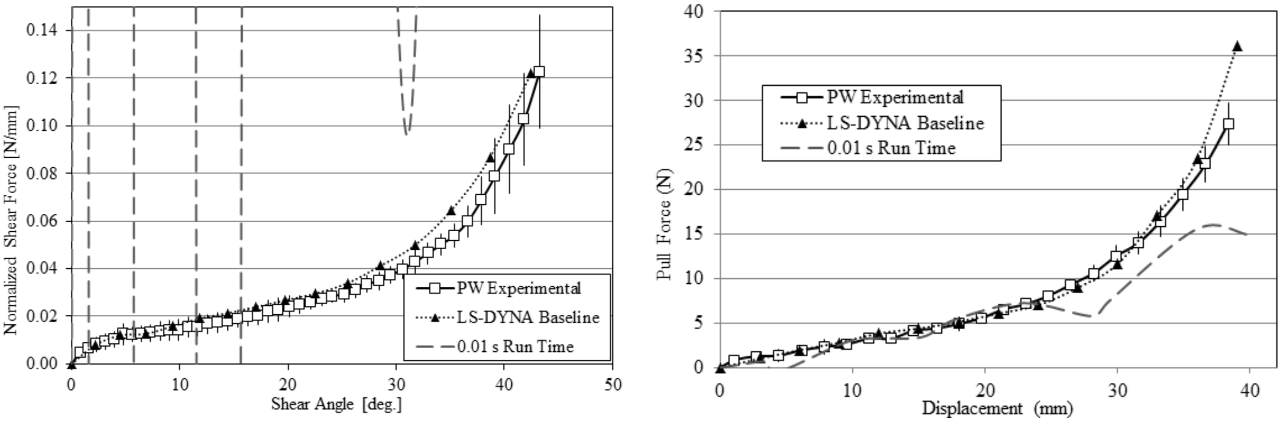
Inertial effects are a common challenge when using an explicit finite element solver to analyze a relatively “slow” process. The explicit finite element solvers are ideally suited to the investigation of high-speed impact and blast scenarios. Compared to these situations, thermoforming is a relatively “slow” process. However, the use of an explicit solver for simulating the forming of a composite is an attractive method because of the robust contact algorithms employed that are not available in implicit solvers. The numerical methods used in the explicit solvers inherently introduce artificial inertial effects into “slow” processes. Therefore, when using an explicit solver for “slow” events, modeling options such as mass scaling, time scaling and damping are frequently required to attenuate high-frequency dynamics resulting from the solver.

The following sections discuss the parametric studies completed for this research to explore the benefits and consequences associated with the various modeling options available in LS-DYNA. The geometry chosen for these studies is a double-dome which was specifically devised for use in an international benchmarking program for comparing forming simulation results among research groups. The plain-weave material model was used for all analyses, and a viscous damping at 20% of critical, as recommended [6], was used throughout the study.

Time Scaling

In an attempt to resolve the convergence issues associated with inertial effects, time scaling was investigated. The model run time was varied so as to change the effective force (i.e., mass times acceleration) experienced by the fabric during the forming process. The results of this time scaling revealed an inversely proportional relationship between simulation time and analysis completion. By decreasing the model end time by a factor of ten (from 0.10 s to 0.01 s), the "free" fabric double-dome model runs to completion and the wrinkling of the free fabric is essentially eliminated.

To determine if decreasing the model run time was a viable solution for the stamping of "free" fabric, the models used for material validations (i.e., shear frame and bias-extension tests) were re-run using a reduced end time. Figure 6 compares the experimental shear frame results and bias-extension results to the baseline model with an end time of 0.10 s and to the model with an end time of 0.01 s. The data show that decreasing the model end time has adverse effects on the results of both the shear frame and bias-extension models. Thus, time scaling is not a viable modeling option for resolving the waves that are a consequence of the explicit solver.

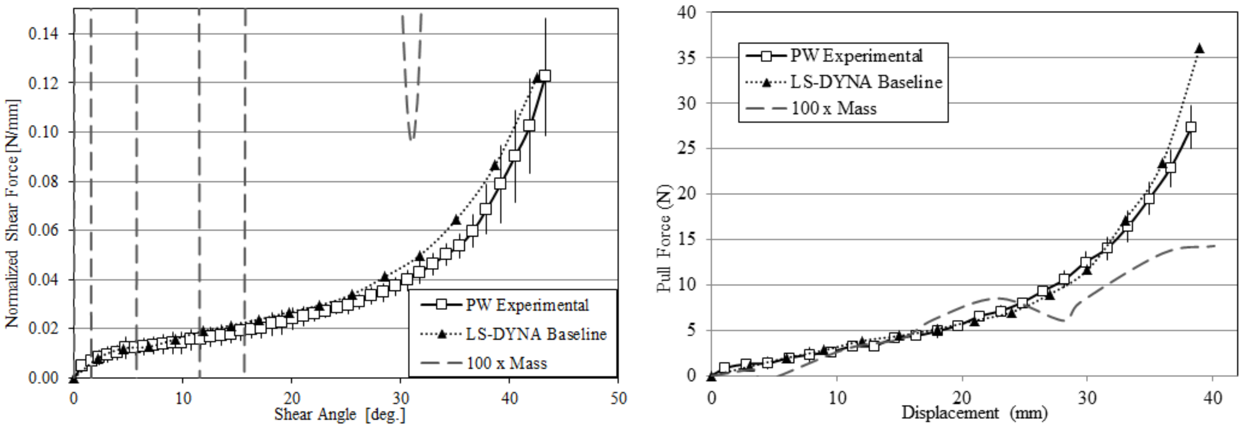


(a) (b)

Figure 6. Comparison of (a) shear frame and (b) bias-extension results with time scaling

Mass Scaling

Similar to the motivation behind investigating time scaling, mass scaling was considered to change the effective force (i.e., mass times acceleration) experienced by the fabric during the forming process. The solver was able to reach a converged solution using mass scaling and the shear frame and bias-extension tests were re-run to determine if increasing the fabric mass would compromise the credibility of the modeling results. Figure 7 compares the model with mass scaled by a factor of 100 to the experimental and baseline shear frame and bias-extension results. The plots show that increasing the model mass significantly alters the results and thus, mass scaling is an unacceptable modeling option.



(a) (b)

Figure 7. Comparison of (a) shear frame and (b) bias-extension results with mass scaling

Global Damping

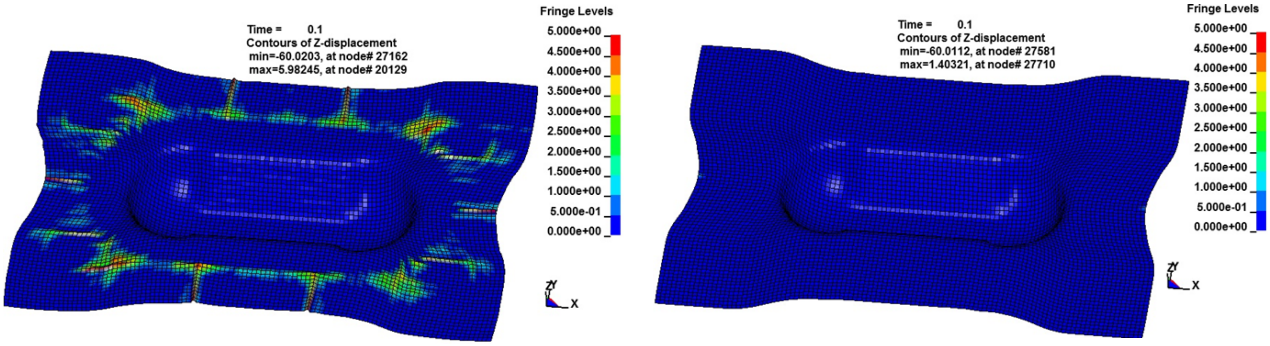
In another attempt to attenuate the inertial effects of the finite element solver, global damping was investigated. Global damping is a mass weighted nodal damping that applies globally to the nodes of deformable bodies and to the mass center of a rigid body [7]. This type of damping can be applied to all parts or to a select set of parts. There are two parameters that need to be defined within LS-DYNA to apply global damping: the first is the amount of damping (VALDMP) and the second is to specify the degrees of freedom that damping is applied (STX-SRZ), i.e. any combination of the three translational (STX, STY and SRZ) and three rotational (SRX, SRY and SRZ) degrees of freedom at a node.

Applying global damping to all the parts of the shear-frame model resulted in an increase in error due to damping being applied to the rigid frame and spherical connection joints. Therefore, it was concluded that the global damping would only be a viable option if it was applied exclusively to the fabric. The VALDMP values studied for the forming of the double dome are shown in Table 1 along with the corresponding percent of model completion.

Table 1. Percent completion of double-dome model for varying global damping

VALDMP	Percent Completion
0	40%
1E2	75%
1E3	100%
1E4	100%
1E5	100%

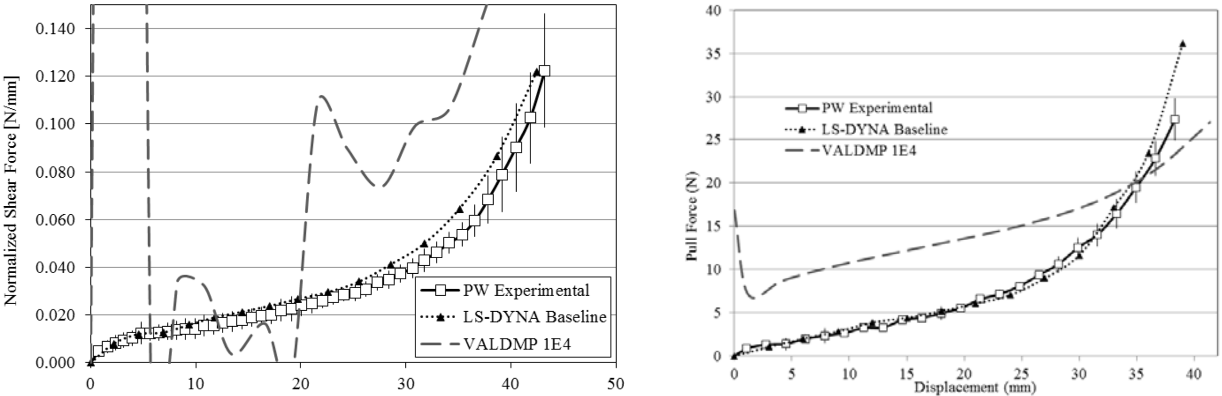
Figure 8 shows the out-of-plane displacement of the fabric for forming simulations with VALDMP values of 1E3 and 1E4. The results show that, even though a VALDMP of 1E3 gives 100% completion for the double-dome model, it does not prohibit the fabric from lifting off the surface of the die and wrinkling out of plane. Although the fabric may wrinkle during the actual forming process, identifying which modeling parameters minimize the fabric wrinkling is one way to determine a potential set of "free" fabric modeling parameters that can aid in the development of a simulation to correlate well with the physical forming process. As shown in Figure 8, the maximum fabric wrinkle height is 5.98 mm and 1.40 mm for global damping values of 1E3 and 1E4, respectively. Therefore, it is concluded that the smallest value of VALDMP to minimize the "free" fabric from lifting off the surface of the die and eliminate out-of-plane wrinkling is 1E4.



(a) (b)

Figure 8. Comparison of double-dome positive z-displacement contours with VALDAMP values of (a) 1E3 and (b) 1E4

Shear frame and bias-extension models were re-run to study the effects of having a global damping value of 1E4. The plots in Figure 9 show how the shear frame and bias-extension results are affected by introducing global damping into the model. The results demonstrate that, although the damping value of 1E4 allows the model to run to completion, it significantly over-predicts the force required to shear the fabric. This over-estimate of the shear force will cause discrepancies in the final calculation of the model's shear angle contour when compared to an experimentally stamped part, and it will also overestimate the stresses in the yarns. As such, global damping is not a viable modeling option.



(a) (b)

Figure 9. Comparison of (a) shear frame and (b) bias-extension results with global damping

Frequency Range Damping

A study of frequency range damping (FRD) was completed in an effort to resolve the artificial wrinkling that occurs when using an explicit solver for modeling the thermoforming process. Frequency-range damping provides approximately constant damping over a user-specified range of frequencies. There are four user-defined parameters that can be varied in this damping study:

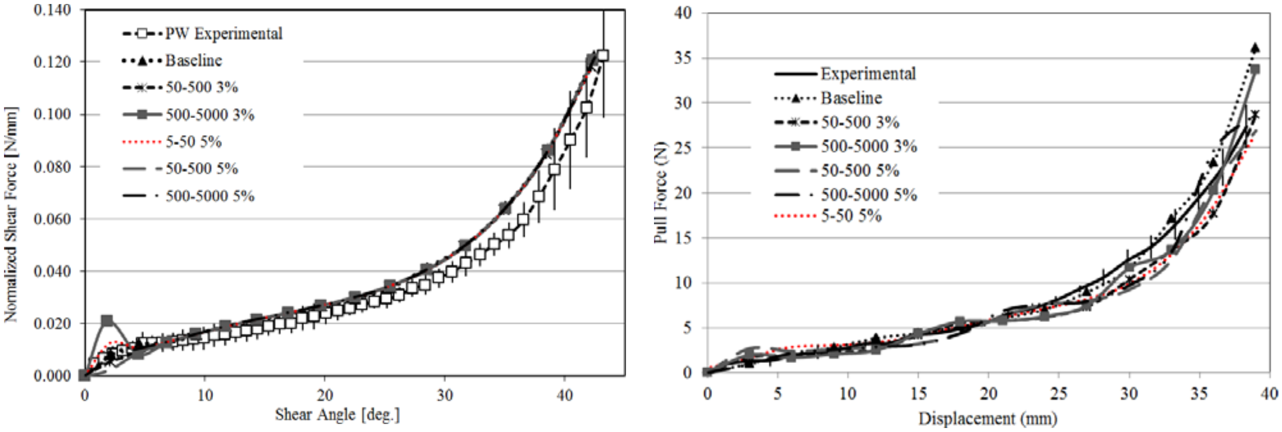
(1) the amount of damping in percent of critical (CDAMP), (2) the lower (FLOW) and (3) upper (FHIGH) bounds of the frequency range and (4) which parts are subject to the damping (PSID).

Frequency range damping was applied to the elements that comprise the fabric in the double-dome model. The values used for this damping study and the respective fabric wrinkle heights are summarized in Table . All nine variations of frequency range damping were sufficient to allow the double-dome model to run to completion. However, the fabric wrinkle height was observed to change with the range and damping values chosen. Based on an acceptable wrinkle height of 0.2 mm, set numbers 5 through 9 in Table 2 were chosen for further investigation to determine an adequate combination of parameters.

Table 2. Percent completion of double-dome model for varying frequency range damping

Set No.	CDAMP [% critical]	Frequency Range Low [Hz]	High [Hz]	Wrinkle Height [mm]
1	1	5	50	4.16
2	1	50	500	3.47
3	1	500	5000	2.45
4	3	5	50	2.20
5	3	50	500	0.17
6	3	500	5000	0.18
7	5	5	50	0.19
8	5	50	500	0.11
9	5	500	5000	0.08

Figure 10a shows the shear frame results for set numbers 5 through 9 in Table 2 which are very similar to the baseline response. One conclusion that can be drawn from these data are that FRD does not compromise the results for a basic fabric characterization experiment, and, thus it is a potential modeling option that should be integrated into the forming simulation to prevent fictitious out-of-plane wrinkling that is purely a consequence of the explicit solver. However, it is inconclusive from these runs as to whether or not there is a best choice for a frequency damping range. Therefore, the bias-extension model results were explored to see if the comparison of experimental and model data could assist in choosing the best combination of frequency range damping parameters. The bias-extension simulation was re-run using the FRD parameters for set 5 through set 9. The resulting load-displacement curves are plotted in Figure 10b alongside the baseline and experimental data. All five of the FRD models correlate well with the experimental and baseline results. A frequency range between 5 Hz and 50 Hz with a damping value of 5% of critical was chosen as the best set of FRD parameters based on the results presented in Table 2 and Figure 10. Figure 11 shows the shear contour for the double-dome stamping model using the predetermined values for frequency-range damping. The contour plot shown agrees with the expected solution, and there is essentially no out-of-plane wrinkling seen in the simulation.



(a) (b)

Figure 10. Comparison of (a) shear frame and (b) bias-extension results for sets 5 through 9

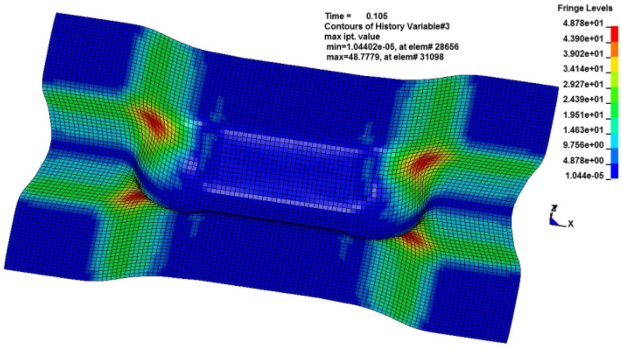


Figure 11. Shear angle contour of double-dome stamping model with frequency-range damping

Conclusions

A finite element model of the fabric was presented based on the experimentally determined properties. The experiments used to calculate the fabric properties were modeled in LS-DYNA for validation of the credibility of the material subroutine. Contact damping parameters were studied within LS-DYNA and were selected to allow for a realistic modeling of the excess fabric during the thermoforming process. Implementation of contact damping helps to eliminate some of the high-frequency dynamics associated with inertial effects that prevented convergence of the model within LS-DYNA.

A parametric study including time scaling, mass scaling, global damping, and frequency range damping was completed to determine the best method to model unconstrained fabric within LS-DYNA. It was ultimately determined that frequency range damping not only allowed the most robust modeling of "free" fabric but it also had minimal effects on the shear frame and bias-extension models used for validation. The implementation of frequency range damping within LS-DYNA allowed for stamping models of unconstrained fabric.

References

1. J. Gorczyca, J. Sherwood, and J. Chen, *Development of a Friction Model for Use in the Thermostamping of Commingled Glass-Polypropylene Woven Fabrics*, Composites Part A, Vol. 38, p. 393-406. 2005.
2. D. Jauffrès, J. Sherwood, C. Morris, and J. Chen, *Discrete mesoscopic modeling for the simulation of woven-fabric reinforcement forming*, International J. of Forming, Vol. 3, Sup. 2, p. 1205-1216, 2009.
3. ASTM Standard D2256/D2256M – 10ε1, 2010, *Standard Test Method for Tensile Properties of Yarns by the Single-Strand Method*, ASTM International, West Conshohocken, PA, 2009, DOI: 10.1520/ D2256_D2256M-10E01, www.astm.org.
4. D. Lussier, *Shear characterization of textile composite formability*. Lowell: UMass, 2002
5. G. Lebrun, M. N. Bureau, and J. Denault, *Evaluation of bias-extension and picture-frame test methods for the measurements of intraply shear properties of PP/Glass commingled fabrics*, Composite Structures, 61:341-352, 2003.
6. B.N. Maker and X. Zhu, *Input Parameters for Metal Forming Simulation using LS-DYNA*, Livermore Software Technology Corporation. Apr. 2000.
7. LSTC, *LS-DYNA Keyword Manual Version 971 R.6.0.0*. 2012.