Finite Element Modeling of Co-Mingled Glass/Thermoplastic Fabrics for Low-Cost/High-Volume Composites Manufacturing

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ABSTRACT

The stamping of co-mingled glass/thermoplastic textiles for manufacturing relatively low-cost/high-volume structural composite automotive parts, e.g. truck beds and floor pans, is extremely attractive. These textile materials have yarns comprised of polymer fibers interwoven with the structural fibers, e.g. fiberglass. By heating the textiles in an oven, the polymer fibers melt and infuse the yarn, thereby removing the need to apply the resin in a separate step. The heated fabric can subsequently be stamped into a structural shape. The difficulty these fabric materials exhibit is that their deformation response exhibits both geometrical and materially nonlinear behaviors. The candidate material being evaluated in this study has a weave structure. The stamping mold for the current research is a hemispherical shape. Several samples of the candidate material were stamped to a variety of depths and over a range of temperatures to see how the sides of the material draw in as the part is being stamped. Splits on the hemispherical portion and wrinkles on the adjacent flat surface were observed. Several material models inherent to LS-DYNA were evaluated and a user-supplied subroutine was incorporated to consider the weave architecture. The correlation of the experimental and finite element results are presented.

INTRODUCTION

Early in history, it was observed that combining different materials resulted in a new material with properties superior to either of the constituents alone. For example, Egyptians reinforced mud bricks with straws, Samurai swords and Damascus gun barrels combined layers of iron and steel for greater strength, Mongols made bows from cattle parts, wood, and silk bonded together and bridges and walls are constructed today of steel-reinforced concrete. Nature also uses the same principle in celery, where the pith surrounds the fibrous cellulose material and gives the celery stalk additional support. These combinations of materials could be called composites in the most general sense, because they consist of two or more identifiable constituents. However, many natural and man-made materials would come under this definition and the category of composites would be too broad. Therefore, a more useful definition of composite would be the combination of a reinforced material, such as a particle or fiber in a matrix (Brent-Strong, 1989).

Some ceramic composites existed as early as the 1920s. In 1945, a glass-reinforced phenolic-nylon-fishing pole was one of the first modern applications of composites. In the last quarter century, the use of composites has increased rapidly, and the indication is that the usage will only continue to increase. The attraction of composites primarily stems from their ability to produce parts that exhibit relatively lighter weight, higher strength/stiffness, corrosion resistance and heat resistance compared to metals. However, these benefits do not come without a price. The manufacturing of composite parts is labor intensive and time consuming. High-performance composite parts to date have not been able to satisfy the high production rates and low cost that the auto industry requires. Currently, compromises in cost and/or time must be made. If composite parts are to proliferate through the automotive industry and begin to replace metal stampings, then high production rates and low costs are required.

Composite parts can be manufactured through several methods by first combining a dry fabric and a resin. The most common methods of making a composite part are through a compression mold (SMC, BMC, DMC), injection mold and liquid mold (RTM, SRIM). Some of these manufacturing processes can take days to manufacture a single part and others are simply unsuitable for making a structural composite part (Hyer, 1998).

A recent and potentially useful development in composites manufacturing is the combination of fibers made from thermoplastic matrix resins with conventional reinforcement fibers–a.k.a.

co-mingled glass/thermoplastic fabrics. The thermoplastic resin is chosen over the thermoset resin because it can be processed more quickly and offers the potential to reduce manufacturing costs. Also, when heated, cross-linking reactions do not occur–eliminating the need to maintain elevated temperature for an extended period of time (Hyer, 1998). The automotive industry has a significant interest in the co-mingled glass/thermoplastic fabrics due to the ease of forming a composite part. One feature that highlights the benefits of these fabric materials is the matched stamp/die mold technique, which is used to form composite parts. There is no need to apply and control the resin in a separate step during the forming process. By heating the fabric, the thermoplastic fibers melt and coat the glass. Therefore, using a plug (male)/cavity (female) mold, the material can then be stamped making the composite part. Fig. 1 shows the stamping machine used at Ford Research Labs to form such composite parts.

The current research has concentrated on characterizing the mechanical properties of these commingled fabrics. The benefit of stamping these fabrics into relatively complex shapes does not come without a price. First, continuous fabric composite laminates tend to suffer from instability problems during processing, e.g., wrinkling as a consequence of fiber buckling due to the property mismatch between rigid fibers and viscous resins at the forming temperature, tearing and fiber swimming. Second, the change of fiber orientation by deformation varies according to the extent to which the material has been deep-drawn. By characterizing and understanding the material behavior, the ability to form a composite part with no defects can be studied using a numerical technique and optimal composite parts can be achieved using a low-cost/high-volume manufacturing process (Kikuchi *et al*., 1997).

Figure 1. Stamping Machine

An FEA of the stamping process can be very effective in modeling the thermoforming process. Computer simulations can capture the overall material behavior, provide information about how various control parameters influence the process and predict final-part geometry, while avoiding the need for trial-and-error testing methods. Figure 2 shows a composite part and how it draws-in on the sides after being formed.

The purpose of this paper is to construct a finite element model of the stamping process using different composite material models for the fabric. A generic model of a flat plate being stamped by a set of hemispherical dies was built using HyperMesh. The potential of modeling the stamping process using LS-DYNA is investigated. The finite element results and the experimental deformations (draw-in) of the fabric are compared. The model was used to evaluate the features of the composite material models included in LS-DYNA and the advantages of incorporating a user-defined material model into LS-DYNA for modeling the stamping process.

Figure 2. Stamped Fabric

APPROACH

A finite element model of the stamping process was constructed to include the fabric, the dies and a binder ring. Fig. 3 is a schematic denoting these components. The stamp/die system for the research is a hemispherical. The molds and the ring binder were constructed as rigid bodies to reduce CPU time. As opposed to modeling the fabric architecture in detail down to the toes (micromechanics approach), the fabric is modeled as a sheet and the net influence of the weave and the resin are considered in a macroscopic sense.

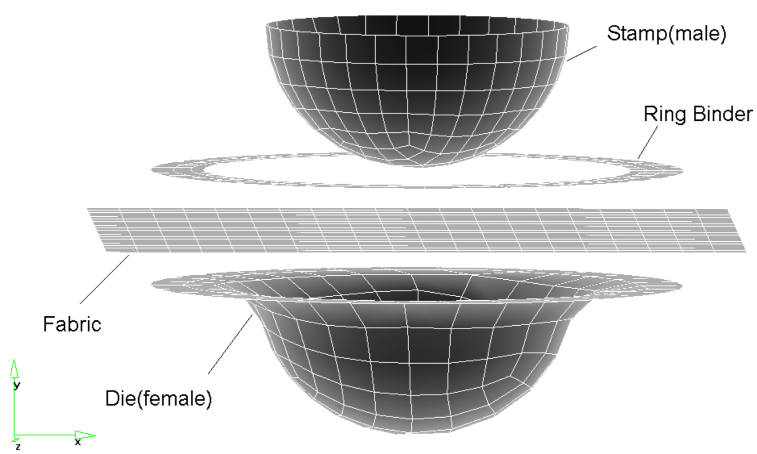


Figure 3. Finite Element Models of Stamping Process Components

Standard Composite Material Models

For the fabric, three different composite material models that are standard with LS-DYNA were evaluated. Specifically the models are:

1. Mat composite failure shell
2. Mat composite Damage
3. Mat enhanced composite damage

All these materials can be used as arbitrary orthotropic materials, i.e. the principal direction of the material can be specified. They are valid for modeling elastic-orthotropic behavior of the fabric using shell elements. The material enhanced composite damage is material type 54. This material is the enhanced version of the composite damage. The two types of failure that can be specified are the Chang-Chang and Tsai-Wu. For the current study, the latter option was chosen.

A variety of boundary conditions were applied on each component as part of a parametric study to consider their impact on the resulting part. A pressure load curve was prescribed to hold the ring binder against the sheet. For the stamp mold, a parabolic concave downward velocity load curve was prescribed to move the stamp down and into the fabric. The fabric boundary conditions were applied to constrain rotation of the in-plane axis. The extent of the draw-in for different material models was visually compared to an actual stamping as depicted in Fig. 4(a).

User-Supplied Material Model

Using the information gained from modeling the stamping process with the three previously discussed composite material models included in LS-DYNA, a user-defined material model is being developed. The orthotropic material models included in LS-DYNA were very useful to start the analysis of modeling the fabric draw-in. However, due to the fabric structure, there are other mechanical behaviors of the fabric that need to be addressed but are not considered in any of the standard material models. The standard composite models do not consider the change in the orientation of the toes as the fabric is stamped out of plane. Furthermore, the toes do not fully distort from mutually orthogonal to parallel, but reach a distortion angle commonly called the locking angle. This locking angle is a function of the tightness of the weave and the size of the individual toes. Second, the solidification of the resin as the fabric contacts the dies results in an instantaneous change in the material properties of the resin. Hence, the forming temperature must be taken into account and the material constants updated accordingly. The user-supplied model uses the contact force as a flag to switch the temperature from that of the oven to that of the die (slightly above room temperature), and, hence, change the material constants. Third, the fibers comprising the individual toes can become compacted as the toes contact one another.

The proposed user-supplied model considers the time-, temperature- and deformation-dependent responses of the fabric. This proposed model is currently being integrated into LS-DYNA via a FORTRAN subroutine. The material model considers the description of the unit cell for the weave under consideration, the width of the yarns, and the evolution in the mechanical behavior of the unit cell as the fabric is deformed.

A relationship for the unit cell volume fraction (V_f) associated with trellis deformation is under development. This relation includes several fabric parameters, such as the angle between the warp and the weft, the yarn size and the yarn spacing. The yarn size and the yarn spacing correspond to the undeformed fabric geometry. The angle between the warp and the weft yarns, θ, evolves with the material deformation. As the material deforms, the unit cell volume fraction changes as function of θ, i.e. (V_f (θ)). The V_f (θ) is then used to find the current material properties of the unit cell of the fabric (McBride, 1997).

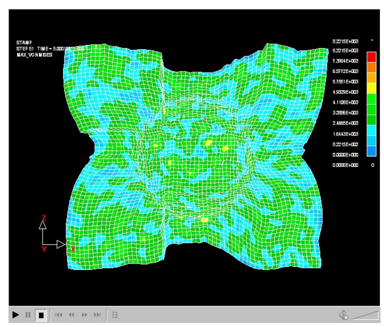
Because the fabric properties for the weave are deformation dependent, it is necessary to track the evolution of the material stiffness as function of the angle between the yarns. To be able to obtain the current average fabric properties at a given level of deformation, an averaging procedure is applied to the unit cell whose microstructure and properties correspond to the current level of fabric deformation. By slicing the yarns of the fabric, the fabric can be discretized into an assembly of unit cells. Each of these slices is presumed to be transversely isotropic with the assumption that the unit cell is uniform through a given slice. However, the orientation with respect to the global coordinate system changes.

An effective piecewise linear relation in the global coordinate system relates the incremental strains to incremental changes in the state of stress for the current unit-cell configuration. The strain-state dependence of the homogenized fabric is associated with the effective constitutive matrix as a function of the current value of the yarn-angle, θ. This effective constitutive matrix is used in an incremental stress-strain relation to describe the average response of the woven fabric to large trellis deformation. The shear strain is used to track the changes in the angle between the warp and weft yarns.

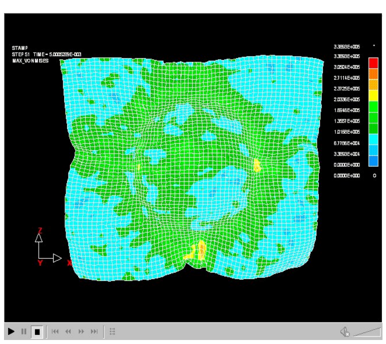
DISCUSSION OF RESULTS

Fig. 4(a) shows the original (experimental) stamped fabric and Figs. 4(b) through (c) are the FEA results with orthotropic materials as noted.

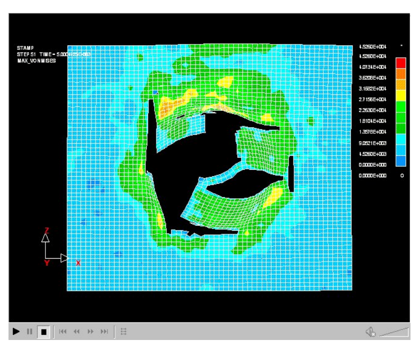
a. Original Stamped Part



b. Material Composite Failure Shell



c. Material Composite Damage



d. Material Enhanced Composite Damage

Figure 4. Comparison of Experimental and LS-DYNA Results

The draw-in for the composite failure shell model (Fig. 4(b)) correlates well with the experimentally stamped part. The composite damage material does not draw-in as much as the failure shell, and, hence, does not appear to correlate well with the experimental stamping. The enhanced composite damage sheet did not draw-in as the stamp mold was lowered– resulting in tearing (failure) in the center of the fabric. This failure may be more a consequence of the prescribed fracture stress, which may have been too low, than it is a limitation of the material model.

The draw-in comparison aids in the development boundary conditions and the choice of a material model to investigate the stamping process numerically. The comparison also characterizes what physical behavior is expected from the material and what parameters such as stamping velocity and ring-binder pressure should be considered.

CONCLUSIONS

A model for the stamping process was constructed and studied using several different orthotropic materials for the fabric. The Failure Shell material draw-in correlated well with the experimental results. The Composite Damage material did not draw-in as much as the Failure Shell, and the Enhanced Composite Damage material does not correlate with the experimental sample. Through these analyses, a sense of how the fabric should draw-in while being stamped was accomplished

However, the main problem is not only to observe and analyze how the fabric draws in as it is being stamped, but also to incorporate a time-, temperature- and deformation-dependent response for the material model. The material model in progress is also being developed in a macroscopic sense. The material model can be integrated into LS-DYNA as a user-supplied material model via a FORTRAN subroutine.

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