SIMULATION OF TRI-AXIALLY BRAIDED COMPOSITES HALF-CYLINDER BEHAVIOR DURING BALISTIC IMPACT

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SIMULATION OF TRI-AXIALLY BRAIDED COMPOSITES HALF-CYLINDER BEHAVIOR DURING BALISTIC IMPACT

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Thesis

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ABSTRACT

The light polymer composite materials with carbon tri-axially reinforcement have been successfully used for fan cases in several jet engine design. Fan case containment must resist blade impact, so failure behavior during high velocity impact is very important. The expensive and time consuming blade-out tests are required by FAA. Both industry and government would like to use realistic numerical simulations of the blade-out events in order to understand the physics of failure and help in the design process. This study describes ability to simulate failure of carbon reinforced tri-axial composite materials used for such jet engine fan cases. The objective of this work is to predict threshold velocities for different fiber orientation in braided tri-axial composite half cylinders impacted by soft projectiles.

The simplified braided through thickness integration point methodology was used to simulate impact event of tri-axial braided composite using LsDyna3D nonlinear FE code. This method is based on unit cell consisting of sub-cells that are modeled by shell elements with local lamination structure. Each integration point of shell element represents different laminae with local fiber orientation.

Composite laminate is represented using standard material model Mat_54 (ENHANCED_COMPOSITE_DDAMAGE), and soft projectile is represented by Mat_181 (SIMPLIFIED_RUBBER). Impact simulation was validated using experimental test results conducted at NASA Ballistic Impact Laboratory for [0°/±60°] fiber
orientation braid. The model parameters were chosen so threshold velocity and damage shape of the simulation correlates well with experimental observations.

The results of parametric studies show that the local minima of threshold velocities are for $[0^\circ/\pm 15^\circ]$ and $[0^\circ/\pm 70^\circ]$ degrees braid and the largest threshold velocity is obtained for the braid with fiber orientation between $[0^\circ/\pm 40^\circ]$ and $[0^\circ/\pm 45^\circ]$. So the jet engine cases should be fabricated using $[0^\circ/\pm 45^\circ]$ braid.
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CHAPTER I

BACKGROUND

1.1 Introduction

One of the heaviest parts of jet engine is the containment case. Advanced braided composite materials can be used to lower the weight of these cases without compromising its safety. GEAE, and Williams International already demonstrated that carbon reinforced braided containment can be used for soft–wall as shown in Figure 1, and hard-wall containment systems. Other companies are in the process of adopting this idea for their designs. One of the critical problems is composite brittleness under high velocity impact conditions. Braided composite was shown to best resist impact delamination and crack propagation under post impact cyclic loads.

Recently, tri-axially braided composites are also used for aircraft primary parts and for components of cars and track. The yarns in tri-axially braided composites are intertwined diagonally, what gives an improved resistance against cracking and delamination during the impact and crash. In fact, the fiber and matrix properties used for braided composites and geometrical parameters such as angle between braided fibers, yarn’s waviness, and tow geometry can drastically modify composite behavior. The research community has a large concern on these problems and they try to develop tools to predict the impact. It was reported in the literature that the matrix in this kind of composite has a large stain rate effect.
1.2 Literature Review - Resin Behavior

The polymers are characterized by rate-dependent response. The linear viscoelastic models have been used to simulate of rate dependent behavior in which combinations of springs and dashpots organized in parallel series may be used to obtain the rate dependent behavior [1]. In case of large strains the response is no longer linear. Nonlinear viscoelastic model has been developed and nonlinear dashpots are incorporated into the constitutive model developed by Cessna and Sternstein [2]. Also the empirical equations may be applied to capture the rate dependent characteristic where the yield stress is shown as a function of strain rate. The other approach of polymer constitutive modeling
focuses on molecular structure. In this case the deformation of a polymer corresponds to the motion of molecular chains above potential energy barriers. The molecular flux is due to applied stress, and the internal viscosity become smaller with applied stress. In that situation the internal stresses may be predicted. It is represented by a resistance of molecular flow that aim to push the material back in the original direction.

Another approach of polymer deformation involves the deformation due to the unwinding of molecular kinks [3]. In that case the constitutive model has been developed and is described as a function of parameters such as activation energy, molecular diameter and angle of rotation. Moreover, the deformation is defined to be a function of state variables representing the resistance to molecular flow. Such a flow is mediated by different mechanisms including the state variable values evolved with stress, inelastic strain and inelastic strain rate.

The optional approach to the constitutive modeling of strain rate dependence of polymers can be done by use of viscoplastic equations that have been developed for metals. These equations may be used directly and with some modification. Bordonaro [4] in his model modified the theory of viscoplasticity in the deformation of polymers applied usually for metals. On the other hand Zhang and Moore [5] has been utilized techniques to develop model of polymer deformation the same way as metals even though it is know that polymers remain different from metals under conditions such as creep, relaxation, and unloading.

Nowadays, the NASA researcher Goldberg [6,7] developed a model to reach the effects of the nonlinear hydrostatic stresses - strain rate dependent deformation of composite materials. The originally designed for metals state variable based constitutive
equations have been modified to obtain of nonlinear, strain rate dependent deformation of polymeric materials. It was shown that the hydrostatic stress is important for polymers. Thus the classical theory of plasticity using an effective stress and inelastic strain can be adequately modified to get equations, which are necessary to compute the components of inelastic strain rate tensor.

Shen has shown [8,9] that an unloading phase is very critical to make a proper impact analysis, of internal energy absorption. This researcher found that the unloading behavior of pure resin is nonlinear. He has also shown that the unloading modulus may be assumed linear but smaller in magnitude in comparison to loading modulus for the constant stain rate. Same conclusions were drawn by Xia [28]. Other researcher, Dubois [10] has replaced Drucker-Prager model by the model of Von Mises to simulate the different behavior of thermoplastic under tension and compression. He considered modification of the Young’s modulus due to damage accumulation process.

1.3 Literature Review - Composites

Recently, scientists are interested in the braided and woven composites have developed analytical tools to predict the elastic behavior of those composites. The simple Ishikawa [11] theory involved one-dimensional model of classical theory, where lamination and iso-stress and iso-strain implementation were combined to establish the elastic behavior of plain weave composites. This theory of simple laminate has been adopted by others researchers such as Wang and Raju [12], Shembekar and Naik [13] to developed two-dimensional analysis of plain weave composite. Even though these theories are still utilized for analysis, there is another one more popular developed by
Tanov and Tabiei [14]. It says that the more accurate analysis may be done by spread the plane weave composite into numerous of four connected sub-cells. That theory applies the process of through the thickness homogenization based on appropriate constant stress and strain to receive the elastic behavior of each of sub-cell. Also the iso- stress and strain assumption is applied to the plane of the composite to calculate the whole effective characteristics. One of other researcher who applied these two similar steps was Pindera [15] and his student Bednarcyk [16]. In their approach local microstructure is represented by a series of sub-cells in the plane of weave. All columns of sub-cells with effective characteristics are established using the General Method of Cells (GMC), which is applied into the plane composite to establish the effective characteristic of the composite materials.

The concept of sub-cells has been adopted by many researchers to examine the mechanical characteristic of some textile composites. For example, Whitcomb and Tang [17] have used finite element analyses to calculated the effective properties of woven composite using full finite element model as a sub-cell pattern. Also Peng [18] and Xue [19] have made many simulations using the sub-cell as a main model of woven composite. In those cases the elastic constants were computed based on homogenization method which was repeated and segmented into sub-cells level. It is hard to predict any damage using the sub-cell and homogenization concept, but this difficulty does not discourage scientist to improve this methods.

One of the researchers who focused on elastic response of braided composite materials is Byun [20]. He has established a geometrical model, which determined a dimension of tri-axial braided composite material based on small group measurable parameters. Constant
stresses are assumed to be present along the length of every tow of fibers. Also stiffness methods with appropriate coordinate transformations have been used to reach the effective stiffness matrix for the whole composite. For example, those techniques were used by Flanagan [21]. He simulated ballistic impact tests of two- and three-dimensional composites (woven and braided materials) by using Lexan® cylindrical projectile. On these tests the failure mode of composite such as matrix cracking, tensile failure and shear failure of fibers were classified in terms of velocity regime, numbers of layers, types and mass of striking projectiles.

Kurath [22] has made the analysis of failure mechanism in woven composite and has shown that these composites demonstrate fiber orientation dependence. On the other hand, Cox [23,24] used micromechanics to predict the failure based on experimental tests.

Because it is hard to predict the failure of composite materials many researchers are focused to understand the impact behavior and damage initiation and progression via experimental investigations.
CHAPTER II
COMPOSITE MECHANICS

2.1 Tri-Axial Composite Model in LS-DYNA

The available composite material models in LS-DYNA [25] are listed in Table-1

Table-1 Composites material models in LS-DYNA (reprinted from Jingyun [26])

<table>
<thead>
<tr>
<th>Material Model</th>
<th>Shell Element</th>
<th>Solid Element</th>
<th>Strain Rate</th>
<th>Failure Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAT 22 (composite_damage)</td>
<td>X</td>
<td>X</td>
<td></td>
<td>Chang-Chang</td>
</tr>
<tr>
<td>MAT 54 (enhanced_composite_damage)</td>
<td>X</td>
<td></td>
<td></td>
<td>Chang-Chang</td>
</tr>
<tr>
<td>MAT 55 (enhanced_composite_damage)</td>
<td>X</td>
<td></td>
<td></td>
<td>Tsai-Wu</td>
</tr>
<tr>
<td>MAT 58 (laminated_composite_fabric)</td>
<td>X</td>
<td></td>
<td></td>
<td>Hashin</td>
</tr>
<tr>
<td>MAT 117 (composite_matrix)</td>
<td>X</td>
<td></td>
<td></td>
<td>No failure, only can used to calculate the elastic response - extensional, bending and coupling stiffness</td>
</tr>
<tr>
<td>MAT 118 (composite_direct)</td>
<td>X</td>
<td></td>
<td></td>
<td>No failure, only can used to calculate the elastic response - extensional, bending and coupling stiffness</td>
</tr>
<tr>
<td>MAT 161 (composite_msc)</td>
<td>X</td>
<td>X</td>
<td></td>
<td>Hashin. Can simulate the delamination</td>
</tr>
</tbody>
</table>
Many composite models have been formulated for shell and solid elements while only one, MAT-161 can be used for solid elements for composite materials with strain rate effect. In this work shell element was used to maximize the effectiveness of the numerical calculations, so material model did not incorporate strain rate dependence.

The most popular failure criteria were developed in the past and reported in the literature as Chang-Chang, Tsai-Wu and Hashin [27] criteria. The models MAT 22 and MAT 54, allows to use Chang-Chang failure criterion, for various failure modes of fibers and matrixes. In this case, the failure modes produced by out-of-plane shear and normal stress are ignored. The very useful model which is based on continuum mechanics and Hashin criteria is MAT 58. Although this model does not allow for the strain rate effect, it may be used in the initial design stage.

2.2 Material Model Used in Simulations

In this case *MAT_54 (ENHANCED_COMPOSITE_DAMAGE) was successfully used to represent polymer composite. This material is arbitrary orthotropic, e.g., unidirectional layers in composite shell structure can be defined. This model is only valid for thin shell elements. By using user defined integration rule represents by card *INTEGRATION_SHELL, the constitutive constants can vary through the shell thickness. This rule specifies the thickness of the layers making up the safety glass. Each integration points of the material is marked as a zero if the layer is glass and as one if the layer is polymer. The lamination shell theory can be activated to properly model the transverse shear deformation. This theory is applied also to correct for the assumption of a uniform constant shear strain through the thickness of the shell.

To represent the soft projectile it was properly used the *MAT_181
(SIMPLIFIED_RUBBER). His deformation during impact is almost the same as the deformation on the real test (Figure 11). This material model provides a rubber model defined by family of curves at discrete strain rate. This family of curves has been got from Michael Bennett who developed this model of soft projectile.

2.3 Conclusions

The LS-DYNA code offers many material models that can be modeled a composite material. It is necessary to examine at least a few of them to find the best representative model, which successfully correlates with the real test. In this case the material such as *MAT_54 correlates well with blade-out tests and properly represents the damage shape and threshold velocity.
CHAPTER III

METHODOLOGY OF SIMPLIFIED BRAIDING THROUGH THICKNES INTEGRATION POINTS

3.1 Introduction

It is known that the new fibers architecture such as tri-axially braided composites with systems of yarns tender better resistance of interlaminar cracking and delaminating during ballistic impact. In fact, the deformation characteristics and failure mechanisms depends on the geometrical parameters and material behavior of composite such as braiding angle, fiber waviness and resin properties. In the previous study [26] the new methodology has been developed to understand how geometrical and material characteristics exert mechanical behavior of composites during high velocity of impact. This chapter shows this method to model composite material with shell elements using Finite Element code (FE) such as LS-DYNA [25,28]. It was successfully used material *Mat_54 which is *Mat_Enhanced_Composite_Damage (described in paragraph 2.2) and Simplified Braiding through Thickness Integration Points methodology. Finally, a linear elastic composite model is applied to pretend the material behavior at the integration point.

3.2 Methodology of LS-DYNA Shell Elements

Final Element method defines each integration point through the thickness of the shell elements. The integration point depends on an angle representing material orientation and
it is not limited to one material layer. For that reason, it is possible that tree integration points may be defined in one ply to represent $+\theta^*/0^-/\theta^*$ to model material such as triaxially braided composites. The parameter $\theta$, which is an angle of bias braiding, is defined by LS-DYNA, *SECTION_SHELL. The procedure of this methodology begins from transformation of stress and velocity strain tensor $d_{ij}$ into a system of material coordination defined by subscript L.

$$\sigma_L = q^T \sigma q$$  \hspace{1cm} (3.1)$$

$$\epsilon_L = q^T \epsilon q$$  \hspace{1cm} (3.2)$$

where $q$ is the orthogonal transformation matrix and $\theta$ an angle of material orientation

$$q = \begin{bmatrix} \cos \theta & -\sin \theta & 0 \\ \sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$  \hspace{1cm} (3.3)$$

It is known, that shell theory assumes a plane stress condition, what means that the normal stress of the middle surface is equal zero. After update, the state of stress in the material coordinate looks like below:

$$\sigma_L^{n+1} = \sigma_L^n + \Delta\sigma_L^{n+1/2}$$  \hspace{1cm} (3.4)$$

For an elastic material, the expression looks like below:

$$\Delta\sigma_L^{n+1/2} = \begin{bmatrix} \Delta\sigma_{11} \\ \Delta\sigma_{22} \\ \Delta\sigma_{12} \\ \Delta\sigma_{23} \\ \Delta\sigma_{31} \end{bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & 0 & 0 & 0 \\ Q_{12} & Q_{22} & 0 & 0 & 0 \\ 0 & 0 & Q_{44} & 0 & 0 \\ 0 & 0 & 0 & Q_{55} & 0 \\ 0 & 0 & 0 & 0 & Q_{66} \end{bmatrix} \begin{bmatrix} d_{11} \\ d_{22} \\ d_{12} \\ d_{23} \\ d_{31} \end{bmatrix}$$  \hspace{1cm} (3.5)$$
The components of the lamina can be calculated from reduced equations:

\[ Q_{11} = \frac{E_{11}}{1 - v_{12}v_{21}} \]  \hspace{1cm} (3.6.1)  

\[ Q_{22} = \frac{E_{22}}{1 - v_{12}v_{21}} \]  \hspace{1cm} (3.6.2)  

\[ Q_{12} = \frac{v_{12}E_{12}}{1 - v_{12}v_{21}} \]  \hspace{1cm} (3.6.3)  

\[ Q_{44} = G_{12} \]  \hspace{1cm} (3.6.4)  

\[ Q_{55} = G_{23} \]  \hspace{1cm} (3.6.5)  

\[ Q_{66} = G_{31} \]  \hspace{1cm} (3.6.6)  

where:

E11 - Young modulus at longitudinal direction

E22 - Young modulus at transverse direction

v12 - Poison ratio

G12 – in plane shear modulus

G23 and G31 - transverse shear modules.

When the stress is updated, it is transformed back to local shell coordinate system:

\[ \sigma = q\sigma^l q' \]  \hspace{1cm} (3.7)
3.3 Methodology of Simplified Braiding through Integration Points - Unit Cell

A tri-axial braided material, where three yarns are twined, forms a single layer of $0^\circ/\pm\theta^\circ$ material. Each yarn with $+\theta^\circ$ direction is crossing suitably under and over the opposite yarn with $-\theta^\circ$ direction. The yarns with $\theta^\circ$ direction are placed between those braided yarns. One way to make proper analyze of braided composites is to examine a unit cell of this material. A unit cell has been defined to be as a smallest unit of repeated fiber architecture [29]. The size of unit cell is not the same for every materials and depends from the size of yarns, the angle of twined these yarns, the number of braided yarns and on diameter of a mandrel. The Figure 2 shows the tri-axial braided composite with architecture of fiber as $0^\circ/\pm60^\circ$. The small marked area represents a one unit cells.

![Figure 2. $0^\circ/\pm60^\circ$ tri-axially braid architecture.](image-url)
Although, the unit cell micromechanical methodology is very popular in modeling of textile composites, Quek [30] shows that this methodology is also difficult to directly implement to model such as the 2D tri-axial composite. The biggest problem comes from difficulties to mesh the unit cell model with proper geometrical system and certitude of fiber volume ratio. The problem is also with the size of unit cell, which in tri-axial braided composite may be so large. Yu and Hassani [31,32] have shown that because of the last difficulty, the micromechanical model of unit cell, which represents homogenize material may not reach the proper damage shape of tri-axial braided composite material during the high velocity impact. In spite of these problems, the methodology of simplified braided through thickness integration point was chosen to model tri-axial braided composite. That is because of promising results from other study [26] and also availability of real test. This method says that the geometry of the braided fiber tow is represented by change of the fiber orientation at every different integration point in the finite element mesh. The reason which makes this method powerful is possibility to divide every unit cell of tri-axial composite material into for sub-cells. Every sub-cell composes of different size fiber tows, fiber orientation, and layer of real geometrical shape and location. This model assumes also that each fiber tow is modeled as unidirectional composite and a whole material structure contains correctly placed all unit cells with sub-cells. That allows for skipping effects of strain rate and matrix-fiber interface.

The Figure 3 shows the fiber architecture of tri-axial braided composite material as a unit cell with sub-cells. To make it clear, this figure does not show the part of matrix. The order of sub-cells is as following:
- sub-cell A -> $0^\circ/0^\circ/-\theta^\circ$ fiber tow and matrix
- sub-cell B -> $\theta^\circ/-\theta^\circ$ fiber tow and matrix
- sub-cell C -> $-\theta^\circ/0^\circ/\theta^\circ$ fiber tow and matrix
- sub-cell D -> $-\theta^\circ/\theta^\circ$ fiber tow and matrix

where:

$\theta$ - angle of bias fiber braiding

The Figure 4 shows the microstructure picture of 2D tri-axially braided composites.

There is no available data of microstructural geometry of braided composites, thus Scanning Electron Microscopy (SEM) was used to measure the geometry of unit cell. The measurement includes length, width, and thickness of fiber tows of different orientation angle. The average data from a few locations have been taken to reduce errors of the measurement. Table 2 shows measured data of geometry fiber tows unit cell $0^\circ/\pm60^\circ$ that have been captured by Scanning Electron Microscopy.

Table 2. The geometry of unit cell ($0^\circ/\pm60^\circ$) (reprinted from Jin [26]).

<table>
<thead>
<tr>
<th></th>
<th>Length (cm)</th>
<th>Width (cm)</th>
<th>Thickness (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub-cell A</td>
<td>0.42</td>
<td>0.51</td>
<td>0.071</td>
</tr>
<tr>
<td>Sub-cell B</td>
<td>0.48</td>
<td>0.51</td>
<td>0.071</td>
</tr>
<tr>
<td>Sub-cell C</td>
<td>0.42</td>
<td>0.51</td>
<td>0.071</td>
</tr>
<tr>
<td>Sub-cell D</td>
<td>0.48</td>
<td>0.51</td>
<td>0.071</td>
</tr>
</tbody>
</table>
Figure 3. Schematic diagram of simplified braided through the thickness integration points methodology. (a) unit cell of tri-axially braided composites (fiber only), (b) mesh scheme of unit cell, (c) specification of fiber tow orientation angle at the through thickness integration points in one unit cell (1Ply) (11 and 22 are in-plane direction, 33 is through the thickness direction) (reprinted from Jin [26])
Figure 4. The image of 2D tri-axially braided composites from SEM.

Each sub-cell has been modeled as a one shell element with a few through the thickness integration points. Also, each angle of braided fibers tow inside the sub-cell has been modeled in unidirectional mode of composite material. The four sub-cells inside every unit cell have been modeled by four shell elements as are presented on Figure 3. Every braiding angle through the thickness integration points has been listed based on its position and stacking sequence. LS-DYNA, *SECTION_SHELL card allows to specify the layers of composite material as a individual integration rules. Every sub-cell may be defined as an element composed from different unidirectional composites with different angle of orientation. LS-DYNA, *INTEGRATION_SHELL card allows to define an adequate bending and membrane stiffness. In this case the weight factor and thickness of
each layer play the important role. Each sub-cell have been defined as 0° unidirectional composite material by *PART card.

- sub-cell A -> three parts are represented by θ°, 0° and -θ° in one ply
- sub-cell B -> two parts are represented by -θ°, and θ° in one ply
- sub-cell C -> three parts are represented by -θ°, 0° and θ° in one ply
- sub-cell D -> two parts are represented by θ°, and -θ° in one ply

Figure 5 shows the mesh scheme with unit cell relations of a local structure. Since this case of the braided composite has 6 braided plies, the sub-cells A and C have 18 integration points; sub-cells B and D have 12 integration points.

![Integration Points Diagram]

Figure 5. The cell with four sub-cells scheme of braiding material through thickness integration points

3.4 The Model of Unidirectional Composite

Every sub cell of tri-axial braided composite material with different location is generalized to be unidirectional material including different size of fiber tow and different fiber volume ratio of local bundle.

The bundle fiber volume ratio has been calculated based on the data from SEM measurement and they are shown in Table 3.
Table 3. the fiber volume ratio of different fiber tow (0°/±60°) (reprinted Jin [26])

<table>
<thead>
<tr>
<th></th>
<th>0° Fiber Volume Ratio</th>
<th>60° Fiber Volume Ratio</th>
<th>-60° Fiber Volume Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub-cell A</td>
<td>85%</td>
<td>62%</td>
<td>62%</td>
</tr>
<tr>
<td>Sub-cell B</td>
<td>n/a</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>Sub-cell C</td>
<td>85%</td>
<td>62%</td>
<td>62%</td>
</tr>
<tr>
<td>Sub-cell D</td>
<td>n/a</td>
<td>50%</td>
<td>50%</td>
</tr>
</tbody>
</table>

To calculate the material properties of the unidirectional composite material, presented below equations have been used:

\[ E_x = V_f E_f + V_m E_m \]  \hspace{1cm} (3.8)
\[ V_x = V_f V_f + V_m V_m \]  \hspace{1cm} (3.9)
\[ \frac{1}{E_y} = \frac{V_f}{E_f} + \frac{V_m}{E_m} \]  \hspace{1cm} (3.10)
\[ \frac{1}{E_s} = \frac{V_f}{E_f} + \frac{V_m}{G_m} \]  \hspace{1cm} (3.11)
\[ G_f = \frac{E_f}{2(1 + \nu_f)} \]  \hspace{1cm} (3.12)
\[ G_m = \frac{G_m}{2(1 + \nu_m)} \]  \hspace{1cm} (3.13)
where:

\[ E_s \] - Young’s modulus along the fiber 11 direction

\[ E_y \] - Young’s modulus in transverse 22 direction

\[ E_s \] - in plane shear modulus

\[ \nu_s \] - in plane Poisson’s ratio (all calculated in material coordinate system 1-2)

\[ V_f \] - fiber volume ratio

\[ V_m \] - matrix volume ratio

\[ E_f \] and \[ E_m \] - corresponding fiber and matrix Young modulus

\[ \nu_f \] and \[ \nu_m \] - corresponding fiber and matrix Poisson ratios

\[ G_f \] and \[ G_m \] - corresponding fiber and matrix shear modulus

In this case it was assumed that the fibers are transversely isotropic and matrix is isotropic. Table 4 shows the material properties that were used in this research.

The fiber producer – Toray supplied the Young modulus, Poisson ratio, tensile strength and failure strain of T700 fiber. The value for transverse Young modulus comes from Sun [33] based on representative carbon fiber data. The Young modulus, Poisson ratio and tensile strength of M36 Epoxy have been provided by producer – Hexply.
Table 4. Material properties of fiber and resin (reprinted from Jin [26]).

<table>
<thead>
<tr>
<th></th>
<th>Toray T700s Fiber</th>
<th>Hexply M36 Epoxy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>1.80</td>
<td>1.17</td>
</tr>
<tr>
<td>Young’s modulus (Gpa)</td>
<td>230</td>
<td>3.5</td>
</tr>
<tr>
<td>Poisson ratio</td>
<td>0.23</td>
<td>0.42</td>
</tr>
<tr>
<td>Tensile Strength (Mpa)</td>
<td>4900</td>
<td>80</td>
</tr>
<tr>
<td>Failure Strain</td>
<td>2.1%</td>
<td>n/a</td>
</tr>
</tbody>
</table>

The four maximum stress failure criteria [34,35] were taken for the unidirectional composite local laminate:

(a) Fiber rupture - tensile fiber model \( \sigma_{11} \geq 0 \)

\[
e^2_j = \left( \frac{\sigma_{11}}{X_f} \right)^2 - 1 \begin{cases} \geq 0 & \text{failed} \\ < 0 & \text{elastic} \end{cases}
\]

(3.14)

When failed, the material is damaged through

\[ E_a = E_b = G_{ab} = \nu_{ba} = \nu_{ab} = 0 \]

(b) Fiber buckling and kinking - compressive fiber model \( \sigma_{11} < 0 \)

\[
e^2_j = \left( \frac{\sigma_{11}}{X_f} \right)^2 - 1 \begin{cases} \geq 0 & \text{failed} \\ < 0 & \text{elastic} \end{cases}
\]

(3.15)

When failed, the material is damaged through

\[ E_a = \nu_{ba} = \nu_{ab} = 0 \]
(c) Matrix cracking under transverse tension and shearing - tensile matrix mode

\[
e_m^2 = \left( \frac{\sigma_{22}}{Y_t} \right)^2 + \left( \frac{\tau}{S_c} \right)^2 - 1 \begin{cases} \geq 0 & \text{failed} \\ < 0 & \text{elastic} \end{cases}
\]

When failed, the material is damaged through

\[ E_b = \nu_{ab} = 0 \quad G_{ab} = 0 \]

(d) Matrix cracking under transverse compression and shearing - compressive matrix mode

\[
e_m^2 = \left( \frac{\sigma_{22}}{2S_c} \right)^2 + \frac{\sigma_{22}}{Y_c} \left[ \frac{Y_c^2}{4S_c^2} - 1 \right] + \left( \frac{\tau}{S_c} \right)^2 - 1 \begin{cases} \geq 0 & \text{failed} \\ < 0 & \text{elastic} \end{cases}
\]

When failed, the material is damaged through

\[ E_b = \nu_{ba} = \nu_{ab} = 0 \quad G_{ab} = 0 \]

Where:

\[ X_t \] - tensile strength in 11 direction

\[ X_c \] - compressive strength in 11 direction

\[ Y_t \] - tensile strength in 22 direction

\[ Y_c \] - compressive strength in 22 direction

\[ S_c \] - in plane shear strength
3.5 The Element Erosion Criteria in LS-DYNA

A simulation of failure has been modeled by elimination of elements form the mesh applying Finite Element (FE) code such as LS-DYNA. This method is called as kill or erosion of elements. The damage of material occurs when some elements are subordinated to critical stress and strain. This method reaches proper results compare to rely tests only when it is used correctly with adequate size of elements and right damage models. A disadvantage of this method is that portion of mass may be lost and causes some problems. The portion of this mass is reconsidered during a contact by *CONTROL_CONTACT card.

In this study, elements are canceled from mesh with fallowing criteria:

- all integration points in one element meet failure criteria
- effective strain damage criteria of element are reached

3.6 Conclusion

The simplified methodology of braiding through thickness integration points is offered to modeled 2D tri-axial braided composites. The size of fiber tow and architecture is examined in this model. The process of defining material constants are discussed in details.
CHAPTER IV
EXPERIMENTAL RESULTS

4.1 Tri-axially Braided Half Cylinder Composite

The $0^\circ/\pm60^\circ$ M36 resin (epoxy system from HEXCEL Composites) containing six layers of a tri-axial braided T700 carbon fiber Half Cylinder was investigated.

The Figure 6 shows the fiber architecture of braided composite. This material was manufactured by A&P Technology and the composite monolith was fabricated by GE Aircraft Engines. The $0^\circ/\pm60^\circ$ braided half-cylinder has 12k flat tow fibers in the $\pm60^\circ$ directions and 24k flat tow fibers in the $0^\circ$ direction. The simulated material is modeled as a fiber-volume fraction of 60%. The volume of fibers in each direction are the same, 33.3% of the fibers are in the $-60^\circ$ direction, 33.3% in the $+60^\circ$ direction, and 33.3% in the $0^\circ$ direction. The lay-up is quasi-isotropic and the cured composite material has a thickness of about 3.2 mm (0.125 in). The half cylinder was fabricated in the form of 112 cm (44 in) diameter half-ring. The spacing between axial tows was measured as 0.89 cm and the spacing between the perpendicular next by unit cells took 0.52 cm for the $\pm60^\circ$ lay-up. The boundary condition was set as a fix all edges. Bolts spaced 2.54 cm (1 in) apart hold the half-ring in place against thick metal rails on all sides (Figure 8) and the slipping of the edges was not a problem with this test fixture [36].
4.2 Gelatin Projectile

The soft projectile is used to simulate the damage and threshold velocity during ballistic impact. Before penetration occurs, the large amount of kinetic energy is transferred into strain energy. In this study the soft projectile used in the impact test was designed from gelatin and micro balloons and its density was set up at 960 kg/m³ [36]. The projectile had the shape of a cylinder 12.7 cm long and 7.0 cm in diameter. The Figure 7 shows a sample of the projectile before and after real test. For true impact test it has been mounted in a sabot and final shot has been made by a 20.3 cm diameter gas gun. The axis of this projectile was equalized along the line of its shot flight. As a results, the flat end of the cylinder reached first contact with the material. The Impact velocity was measured accurately thanks to digital technique such as a high-speed video camera with the view perpendicular to the line of flight. At first, the projectile has flattened into a disk, and next it broke up to small pieces.
The Figure 7b shows the projectile behavior during intermediate velocities.

Figure 7. The gelatin projectile behavior (a) before, (b) during and (c) after impact.

4.3 Results of Ballistic Impact Test

All ballistic tests discussed in this chapter were made by Balistic Impact Laboratory at NASA Glenn Center [36,37,38,39]. Two half-rings were tested using the set up shown in Figure 8a. The half-ring composite has been fabricated as the 0° fibers oriented circumferentially in the fixture. The damaged shape after a test at 150 m/s (492 ft/s) is shown in Figure 8b. The damage is located all around the initial contact area, so because of this it is possible to customize three separate impact tests on each half-cylinder. This test does not involve a problem with slipping of the edges out of the fixture unlike a test with composite plates. The threshold velocity of penetration was observed as a range of 133 m/s (436 ft/s) and 138 m/s (454 ft/s). The cracks were observed initially as propagation from the initiation site in a direction transverse to the 0° fibers rather than along the ±60° fibers. As the cracks reach a location near the edge of the initial impact region, the every of transverse cracks split out into two cracks that move a little distance
along the ±60° directions. These cracks turn again to move along 0° fibers. Finally, the square flaps open by typesetting along a line transverse to the 0° fibers.

Figure 8. Composite targets mounted in the impact test fixtures. 112 cm (44 in) diameter half-ring
Figure 9. Composite half-ring after impact at 150 m/s (492 ft/s).
CHAPTER V
THE SIMULATION OF BALLISTIC IMPACT

5.1 Introduction

The method of simplified braiding through thickness integration points has been developed to model the 2D tri-axial braided composite under high velocity impact loading. This method has been implicated to FE code such as LS-DYNA [24] and was successfully used to simulate ballistic impact behavior on the fiber 0°/±θ° architecture braided composite. The simulation results have been compared with right experimental test with two aspects: deformation and threshold velocity.

5.2 Composite LSDYNA Model

The braided composites have been modeled using the method specified in Chapter 3. To get the same results like from real test the *MAT ENHANCED COMPOSITE DAMAGE was chosen to model the braided tri-axial composite material and *MAT_SIMPLIFIED_RUBBER to model the LaGrange soft project tile. This model has been described in detail in paragraph 2.2.

5.3 Boundary Condition

In this case all edges were fixed. In LSDYNA the card such as *BOUNDARY_SPC_SET was chosen to define all boundary condition.
5.4 Contact Algorithm in LSDYNA

In this case *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE was successfully chosen to define a contact behavior between projectile and composite half-ring. This algorithm is developed by Taylor and Flanagan [1989]. It involves a two pass symmetric approach with partition parameter $\beta$. This parameter is set between -1 and +1 and corresponds to one way treatments with the master surface accumulating mass and forces from the slave surface for $\beta=1$ and opposite for $\beta=-1$. In this approach the accelerations, velocities, and displacements are first updated to configuration without accounting for interface intersection. After the update, the penetration force is calculated for the slave node as a function of the penetration distance $\Delta L$ correlated to the normal vector to the master surface.

5.5 Time Step in LSDYNA

The time step size roughly corresponds to a transient time of an acoustic wave through an element using the shortest distance. For stability reason the scale factor is set up to a value of 0.90. For the shell elements, the time step size is calculated as:

$$\Delta t = \frac{L_s}{c}$$  \hspace{1cm} (5.5.1)

where:

$\text{L}_s$-characteristic length

c-sound speed through a particular material
\[
c = \sqrt{\frac{E}{\rho(1-\nu^2)}} \quad (5.5.2)
\]

\[
L_s = \frac{(1+\beta)A_s}{\max(L_1, L_2, L_3, (1-\beta)L_4)} \quad (5.5.3)
\]

where:

\(\beta=0\) for quadrilateral and \(=1\) for triangular shell elements

As – the area of element

Li (i=1…4) – the length of sides defined shell element

The largest step time causes a smaller solution time, but scale factor larger than 0.90 often guide to instabilities.

5.6 Elements in LSDYNA

Each integration point through the shell thickness, typically not limited to one point per ply, requires to be defined as a orientation angle of that point. The mesh in this case was modeled by 30,600 quadrilateral shell elements. Larger number of elements causes the larger solution time, but it provides much more adequate results with specific details.

5.7 The Validation of Penetration Threshold Velocity

Impact of the composite half-cylinder has been simulated for velocities range from 100 m/s (3937 in/s) to 200 m/s (7874 in/s). The penetration threshold was determined to be between 129 m/s and 134 m/s.
Table 5. Penetration threshold velocity comparison.

<table>
<thead>
<tr>
<th>Penetration threshold velocity (m/s)</th>
<th>Experimental result</th>
<th>LSDYNA simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>half-ring  $0^\circ/\pm60^\circ$</td>
<td>133 – 138 m/s</td>
<td>129 – 134 m/s</td>
</tr>
</tbody>
</table>

Because the threshold velocity and the damage shape, which will be shown later, is almost the same compared to real test, the threshold velocity can be predict for various fiber tow angles of the same composite material. The all results of prediction of projectile velocity are presented in Figure 17.

5.8 The Validation of Soft Projectile Deformation

Figure 10 shows the deformation behavior of projectile. When the contact between projectile and half ring begins, the projectile was stepwise crushed into the panel and captured the shape of circle and was similar to observed in high speed video composite test.
Figure 10. The deformation of soft projectile at velocity as 128 m/s

5.9 The Validation of Tri-axially 0° ±60° Half-Ring Composite Failure

The Figures 11-16 show damage progression of M36 [0°/±60°] half-cylinder during impact velocity at 150 m/s. The crack was initiated in the same place as in the real test, at the location that was close to the impact center. The growing of cracks propagated from the initiation site into a transverse direction along the 0° fibers rather than the ±60° fibers. When the cracks get a location near the edges of the cylinder, each of them split into two cracks that propagated along the ±60° directions. Next, these cracks turn again along 0°
fibers near the edge boundaries. Finally, square flaps have been opened. The Figures 12 shows all the stages described above.

Figure 11. LS-DYNA simulation of damage pattern of M36\([0^\circ/\pm 60^\circ]\) half-ring at impact velocity of 150 m/s at t=0s
Figure 12. LS-DYNA simulation of damage pattern of M36 [0°/±60°] half-ring at impact velocity of 150 m/s at t= 0.00014472s

Figure 13. LS-DYNA simulation of damage pattern of M36 [0°/±60°] half-ring at impact velocity of 150 m/s at t= 0.00041489s
Figure 14. LS-DYNA simulation of damage pattern of M36 $[0^\circ/\pm60^\circ]$ half-ring at impact velocity of 150 m/s at $t=0.00081495s$

Figure 15. LS-DYNA simulation of damage pattern of M36 $[0^\circ/\pm60^\circ]$ half-ring at impact velocity of 150 m/s at $t=0.00157s$
The picture below shows in details the moment of cracking when the cracks split into two cracks and travel short distance along /±60° direction.

Figure 16. LS-DYNA simulation of damage at the time when the cracks split out.
5.10 Prediction of Threshold Velocity of Tri-axially Half-Ring Composite

Figure 17. The threshold velocity of tri-axial braided half-cylinder with various angles of biases.
5.10.1 Comparison the Threshold Velocities of Tri-Axially Half-Ring with the Flat Panel 

The Figure 18 shows the threshold velocity for tri-axially composite flat panel with various angles of biases. The material properties are both the same for the half-ring and flat panel.

![Parametric Study - Flat Plate](image)

Figure 18. The threshold velocity of tri-axial braided plate composite with various angle of biases.
The trend of the penetration threshold for half-cylinder is very similar to the trend of penetration threshold for 0°/±60° flat panel. Figure 19 shows the comparison of these two materials.

Figure 19. The comparison of threshold velocity between tri-axial braided plate composite and tri-axially half-cylinder with various angles of biases.
5.11 Prediction of Damage Shapes of Tri-axially Half-Ring Composite

Figure 20. The deformation of 0°/±15° biases geometry tri-axially braided half-ring composite during threshold velocity value of projectile’s speed \([t=0.001s]\)

Figure 21. The detail of deformation of 0°/±15° biases geometry tri-axially braided half-ring composite during threshold velocity value of projectile’s speed \([t=0.001s]\)
Figure 22. The deformation of $0^\circ/\pm30^\circ$ biases geometry tri-axially braided half-ring composite during threshold velocity value of projectile’s speed [$t=0.0002s$]

Figure 23. The deformation of $0^\circ/\pm30^\circ$ biases geometry tri-axially braided half-ring composite during threshold velocity value of projectile’s speed [$t=0.00064s$]
Figure 24. The deformation of $0^\circ/\pm30^\circ$ biases geometry tri-axially braided half-ring composite during threshold velocity value of projectile’s speed [$t=0.001s$]

Figure 25. The deformation of $0^\circ/\pm35^\circ$ biases geometry tri-axially braided half-ring composite during threshold velocity value of projectile’s speed [$t=0.00016s$]
Figure 26. The deformation of $0^\circ/\pm35^\circ$ biases geometry tri-axially braided half-ring composite during threshold velocity value of projectile’s speed [$t=0.00024\text{s}$]

Figure 27. The deformation of $0^\circ/\pm35^\circ$ biases geometry tri-axially braided half-ring composite during threshold velocity value of projectile’s speed [$t=0.00043\text{s}$]
Figure 28. The deformation of $0^\circ/\pm 35^\circ$ biases geometry tri-axially braided half-ring composite during threshold velocity value of projectile’s speed \([t=0.001s]\)

Figure 29. The deformation of $0^\circ/\pm 40^\circ$ biases geometry tri-axially braided half-ring composite during threshold velocity value of projectile’s speed \([t=0.00015s]\)
Figure 30. The deformation of 0°/±40° biases geometry tri-axially braided half-ring composite during threshold velocity value of projectile’s speed \( t=0.00024\text{s} \)

Figure 31. The deformation of 0°/±40° biases geometry tri-axially braided half-ring composite during threshold velocity value of projectile’s speed \( t=0.00064\text{s} \)
Figure 32. The deformation of $0^\circ/\pm40^\circ$ biases geometry tri-axially braided half-ring composite during threshold velocity value of projectile’s speed [$t=0.001s$]

Figure 33. The deformation of $0^\circ/\pm45^\circ$ biases geometry tri-axially braided half-ring composite during threshold velocity value of projectile’s speed [$t=0.00024s$]
Figure 34. The deformation of $0^\circ/\pm45^\circ$ biases geometry tri-axially braided half-ring composite during threshold velocity value of projectile’s speed [$t=0.00064s$]

Figure 35. The deformation of $0^\circ/\pm45^\circ$ biases geometry tri-axially braided half-ring composite during threshold velocity value of projectile’s speed [$t=0.001s$]
Figure 36. The deformation of $0^\circ/\pm 50^\circ$ biases geometry tri-axially braided half-ring composite during threshold velocity value of projectile’s speed \( t=0.00043\text{s} \)

Figure 37. The deformation of $0^\circ/\pm 50^\circ$ biases geometry tri-axially braided half-ring composite during threshold velocity value of projectile’s speed \( t=0.00064\text{s} \)
Figure 38. The deformation of $0^\circ/\pm 50^\circ$ biases geometry tri-axially braided half-ring composite during threshold velocity value of projectile’s speed [$t=0.001s$]

Figure 39. The detail of deformation of $0^\circ/\pm 50^\circ$ biases geometry tri-axially braided half-ring composite during threshold velocity value of projectile’s speed [$t=0.00046s$]
Figure 40. The deformation of $0^\circ/\pm 55^\circ$ biases geometry tri-axially braided half-ring composite during threshold velocity value of projectile’s speed [$t=0.00043s$]

Figure 41. The deformation of $0^\circ/\pm 55^\circ$ biases geometry tri-axially braided half-ring composite during threshold velocity value of projectile’s speed [$t=0.001s$]
Figure 42. The detail of deformation of $0^\circ/\pm 55^\circ$ biases geometry tri-axially braided half-ring composite during threshold velocity value of projectile’s speed [$t=0.00082s$]

Figure 43. The deformation of $0^\circ/\pm 65^\circ$ biases geometry tri-axially braided half-ring composite during threshold velocity value of projectile’s speed [$t=0.00043s$]
Figure 44. The deformation of $0^\circ/\pm 65^\circ$ biases geometry tri-axially braided half-ring composite during threshold velocity value of projectile’s speed [$t=0.00064s$]

Figure 45. The deformation of $0^\circ/\pm 65^\circ$ biases geometry tri-axially braided half-ring composite during threshold velocity value of projectile’s speed [$t=0.001s$]
Figure 46. The detail of deformation of $0^\circ/\pm 65^\circ$ biases geometry tri-axially braided half-ring composite during threshold velocity value of projectile’s speed [$t=0.00068\text{s}$]

Figure 47. The deformation of $0^\circ/\pm 70^\circ$ biases geometry tri-axially braided half-ring composite during threshold velocity value of projectile’s speed [$t=0.00043\text{s}$]
Figure 48. The deformation of $0^\circ/\pm70^\circ$ biases geometry tri-axially braided half-ring composite during threshold velocity value of projectile’s speed \([t=0.00064s]\)

Figure 49. The deformation of $0^\circ/\pm70^\circ$ biases geometry tri-axially braided half-ring composite during threshold velocity value of projectile’s speed \([t=0.001s]\)
Figure 50. The detail of deformation of $0^\circ/\pm 70^\circ$ biases geometry tri-axially braided half-ring composite during threshold velocity value of projectile’s speed [$t=0.00067s$]

Figure 51. The deformation of $0^\circ/\pm 75^\circ$ biases geometry tri-axially braided half-ring composite during threshold velocity value of projectile’s speed [$t=0.00043s$]
Figure 52. The deformation of $0^\circ/\pm 75^\circ$ biases geometry tri-axially braided half-ring composite during threshold velocity value of projectile’s speed [$t=0.00064s$]

Figure 53. The deformation of $0^\circ/\pm 75^\circ$ biases geometry tri-axially braided half-ring composite during threshold velocity value of projectile’s speed [$t=0.001s$]
Figure 54. The detail of deformation of 0°/±75° biases geometry tri-axially braided half-ring composite during threshold velocity value of projectile’s speed [t=0.00053s]

Figure 55. The deformation of 0°/±85° biases geometry tri-axially braided half-ring composite during threshold velocity value of projectile’s speed [t=0.00043s]
Figure 56. The deformation of $0^\circ/\pm 85^\circ$ biases geometry tri-axially braided half-ring composite during threshold velocity value of projectile’s speed [$t=0.00064\text{s}$]

Figure 57. The deformation of $0^\circ/\pm 85^\circ$ biases geometry tri-axially braided half-ring composite during threshold velocity value of projectile’s speed [$t=0.001\text{s}$]
Figure 58. The detail of deformation of $0^\circ/\pm85^\circ$ biases geometry tri-axially braided half-ring composite during threshold velocity value of projectile’s speed [$t=0.00028s$]
The next pictures show that there are only slight differences of material behavior such as
59) total energy, 60) x-stress, 61) y-stress, 62) z-displacement, and 63) projectile velocity
between /±60° and /±45° biases direction.

Figure 59. The difference of total energy between tri-axial composite with /±60° and
/±45° direction
Figure 60. The difference of x-stress between tri-axial composite with /±60° and /±45° direction.

Figure 61. The difference of y-stress between tri-axial composite with /±60° and /±45° direction.
Figure 62. The difference of z-displacement between tri-axial composite with /±60° and /±45° direction.

Figure 63. The difference of projectile velocity between tri-axial composite with /±60° and /±45° direction.

The main difference between both directions is the THRESHOLD velocity which is more
than 50%. The deference is presented as 130 m/s for composite with 60 degree versus 195 m/s for composite with 45 degree. It was shown in Figure 17.

5.12 Prediction of Projectile Behavior

Figure 64. The projectile behavior of 0°/±45° biases geometry tri-axially braided half-ring composite during 200m/s impact – front view [t=0.001s]

Figure 65. The projectile behavior of 0°/±45° biases geometry tri-axially braided half-ring composite during 200m/s impact – top view [t=0.001s]
Figure 66. The projectile behavior of $0^\circ/\pm 60^\circ$ biases geometry tri-axially braided half-ring composite during 200m/s impact – front view [t=0.001s]

Figure 67. The projectile behavior of $0^\circ/\pm 60^\circ$ biases geometry tri-axially braided half-ring composite during 200m/s impact – top view [t=0.001s]
The pictures presented above show that the gate of half-cylinder composite with 0°/±45° biases geometry is fully opened. Also it is observed that the damage in this configuration has a circuit shape rather than a slit. The different damage shape at the same projectile speed [200 m/s] has configuration of 0°/±60° composite. The gate is not fully opened and the damage looks like an incision. Because of those it may be assumed that the projectile meet a larger resistance into 0°/±60° geometry, so it may easily goes through the composite with 0°/±45° biases configuration. To confirm this assumption it is necessary to make more simulations as a future work.

5.13 Comments of Failure Types

It was observed two different type propagation of crack. For the range from 0° to 0°/±40° biases direction the damage shape starts parallel to 0°fibers direction. This course of failure comes from Matrix Driven Failure criteria, which say that the matrix failed first based on fiber geometry. For the range from 0°/45° to 0°/±90° the damage shape starts transverse to 0°fibers direction. It is because of Fiber Driven Failure criteria. The point of 0°/±40° <-> 0°/±45° changes transition failure through fiber and also have a biggest threshold velocity. The fiber length is the largest exactly in this point, so for other geometries they are shorter and do not resist that much.

5.14 Conclusions

Ballistic impact on braided half-cylinder composites was simulated using the simplified braiding through thickness integration point methodology. LS-DYNA simulation results show that this model can capture very properly the failure behavior of material used in real test. Specifically, LS-DYNA simulation captured the damage shape with cracking direction for 0°/±60° and the threshold velocity of braided composite.
There is a small difference between material behavior such as x, y stress, z-displacement, projectile velocity, and total energy for /±60° and /±45° direction. The main difference between above directions is the threshold velocity which is more than 50%.

The characteristic of threshold velocity shows that the composites with 45 degree of biases are more resistant than materials with 60 degree. However, the projectile behavior needs more simulations that may give some answers for elementary question: which geometry of tri-axially composite material is safer?
CHAPTER VI

CONCLUSIONS

In this study the explicit finite element models have been used to examine the deformation and to predict the failure for 2D tri-axially braided composite material under high velocity impact. The simplified methodology of braiding through thickness integration points is offered to model this composite. The unit cell of braided composites has been separated into four sub-cells, and each of them was modeled by utilizing one shell element with the several through thickness integration points. Every one has represented an orientation of different fiber bundle. The shell element developed by Belytschko-Lin-Tsay [28], which is used in LS-DYNA, allows to imply the user’s rules. It may be applied to model multi layers composites. The establishment of composites material constants has also been described in details.

The ballistic impact on braided half-ring composite was simulated by the simplified braiding methodology using sub-cells techniques. The LS-DYNA results show that this model may properly reach the deformation as a failure shape and cracking direction and threshold velocity of composites. The damage size, shape, and the cracking walk order were very similar to the original test. Finally, the innovative method of modeling is effective and may be successfully used with complex high impact simulation. The main conclusion of this study is fact that composites with 45 degree of biases are more
resistant then composite with 60 degree. The penetration threshold velocity is larger as 50% for 45 degree of biases geometry rather than 60 degree. However, it is necessary to make more particular simulation because of projectile behavior.
CHAPTER VII
FUTURE WORK

The main part of this research focuses on the simulation for tri-axial braided composite during ballistic impact. The important role of modeling those materials is to reach as close as possible the material behavior such as failure shape and threshold velocity. It is very difficult to predict the damage shape because the materials properties, especially polymers, have very complex structure and many different techniques and material models may be applied to get proper failure shape. In fact it is almost not possible to reach the adequate failure shape without data from real test and this point may be developed as a future work. To get the right prediction using only a simulation would save a lot of money and time which are required for the test. Obtaining the prediction of material failure at certain fibers configuration would be advantageous, since it might be applied for other material configurations without performing real tests.
REFERENCES


