Progressive Failure Micromechanical Modeling of 3D Woven Composites

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Nomenclature

\[ \begin{align*}
\mu\text{CT} & = \text{micro-computed tomography} \\
DFMA & = \text{Digital Element Analysis Fabric Mechanics Analyzer} \\
\dot{\varepsilon} & = \text{Strain rate} \\
CDM & = \text{Continuum Damage Mechanics} \\
\sigma_n & = \text{Normal stress} \\
\tau_{nl} & = \text{Longitudinal shear stress} \\
\tau_{nt} & = \text{Transverse shear stress} \\
RVE & = \text{Representative Volume Element}
\end{align*} \]

Abstract

An effective materials by design approach has been detailed and exercised to expedite the development and insertion of 3D fabrics and composites in various structural and protective systems. Previous research efforts have identified a family of advanced, 3D woven composite reinforcements which show promise for multiple applications. These multi-layer, integrally woven designs have significantly improved through-thickness properties. The higher through-thickness tensile strengths are a result of additional fibers, oriented in the z-direction, which must be fractured for ultimate failure of the structure. On the other hand, the through thickness shear strengths are strongly dependent on the matrix cracking and yarn-to-yarn interface debonding within the 3D fiber composites. Consequently, properly designed 3D reinforcements can significantly reduce the propagation of delamination commonly induced by severe lateral impact, and thus can greatly enhance the damage tolerance of composite structures.

The proposed approach uses computational methods, rather than experimental observations, to generate complex 2D and 3D composite architectures at the filament level using the digital element approach. The fiber filament model is then idealized as a solid yarn model and meshed for finite element analysis using commercial software. Micromechanics analysis was then used to model the progressive failure response of the composites subjected to loading at various quasi-static and dynamic strain rates, with the results validated through experimentation. Analysis of constituent properties and weave architecture was completed and used to make design recommendations for improved material response for composites subjected to ballistic impact. This approach provides a potential for drastically reducing the design cycle time by eliminating the need to fabricate each design architecture, allowing for reduced cost as well as an increase in the design scope over multiple variations in weave pattern.

I. Introduction

The need for efficient structures with enhanced ballistic capability in various protective and structural applications is persistent. Innovative structural composite materials must be developed that offer both efficient structural performance and resistance to ballistic damage initiation and propagation, as compared to state-of-the-art composite laminates, for current protective applications. Traditional composite laminates absorb energy primarily as axial tensile strain energy during ballistic impact$^1,^3$ Therefore, high specific axial tensile properties are desirable for these material systems. However, during an impact event, structures are also subjected to intense lateral compressive and lateral shear stresses. As a result of the combination of loading, a composite structure may fail

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under ballistic loading without absorbing the optimal axial tensile strain energy due to the relatively low transverse stiffness and strength.

Previous research efforts have identified a family of advanced, 3D woven composite reinforcements which show promise for applications in airframes requiring high ballistic efficiency. These multi-layer, integrally woven designs have significantly improved through-thickness properties. The higher through-thickness tensile strengths are a result of additional fibers, oriented in the z-direction that must be fractured for ultimate failure of the structure. Properly designed through-thickness reinforcements can also significantly reduce the propagation of delamination commonly induced by severe lateral impact, and thus can greatly enhance the ballistic damage tolerance of composite structures.

Traditionally, a fabric micro-geometry is established from a series of micrographs of consecutively sliced thin sections of a composite. Based upon observations, yarn cross-sections are often simplified as elliptical or lenticular shapes with constant cross-sectional area. The simplified micro-geometry is then used to establish the associated finite element model. However, this simplified geometry fails to accurately represent 3D textile fabrics with a more complex topology that have been developed recently, including various tow structures that are used in the weaving process. In many 3D fabrics, yarn cross-sections vary along the axial direction, so cross-section shapes cannot be adequately simplified as elliptical or lenticular. Alternately, due to advancements in µCT scan technology, it is possible to generate the 3D yarn geometry directly from 3D µCT scan images of composites. However in this case, composites need to be made before the fiber architectures can be determined, resulting in increased cost and time over the design cycle.

An effective materials by design approach has been detailed and exercised at the Army Research Laboratory (ARL) to expedite the development and insertion of 3D fabrics and composites in various structural and protective systems. The approach uses computational methods, rather than experimental observations, to generate and model the initiation and progression of damage in the matrix, yarn, and interface of 2D and 3D composite structural materials. This generation of realistic weave patterns from computational simulations has drastically reduced the design cycle time, allowing for reduced cost as well as an increase in the design scope over multiple variations in weave pattern.

II. Methods

A. Composite Micro-Geometry Creation

A hierarchical procedure has been employed to establish the finite element micromechanical model to properly represent the deformation distribution of fiber tow geometry. The approach consists of a tri-level modeling process, which includes the filament, yarn and layer level modeling procedures outlined in Fig. 1. A typical building procedure of a finite element model from initial design to final mesh for a 6% through-thickness orthogonal weave composite is shown in Fig. 2. The process starts from the use of a fabric filament level modeling code, Digital Element Analysis Fabric Mechanics Analyzer (DFMA), developed at Kansas State University under the support of ARL to establish the micro-geometry of 3D fabrics. In the code, the filament-based fabric geometry model was generated by modeling textile processes and fabric deformation based upon inherent textile physics, such as yarn-to-yarn and fiber-to-fiber interactions. The code treats a small section of each representative fiber as a single digital element; each digital element is then pinned together and allowed to deform freely creating a fully flexible chain. With this configuration the stiffness matrix of the digital element is the same as that of a 3D truss element. The procedure is then used to create a desired initial yarn geometry based on a desired topology shown in Fig. 2. Initially, each yarn is represented by a single filament with the designed yarn cross-sectional area. This topology is stretched with a desired fabrication load and then is relaxed to compute the deformed 3D fabric preform. In the next step, a selected number of representative fibers are used to replace each initial single-fiber yarn while its cross-sectional area remains the same. The fiber bundles are then loaded to the desired tension and relaxed. The weave geometry is put through a series of relaxation steps with increased number of fibers within each yarn with the same cross-sectional area. The final configuration is determined when the yarn deformation is saturated between two consecutive loading and relaxation steps.

The fabric filament model was then converted into a yarn-based micro-geometry model in which each deformed yarn is considered as a continuum shown in Fig. 2. This process was completed in two steps; initially a cylinder of a defined radius is revolved about the yarn bundle and the center point of the revolving cylinder is recorded. Next the center point line is used as a bounding surface in which the cylinder is then revolved within, where the center point is again recorded, creating a solid volume representing the fiber tow. Fig. 3 illustrates the two-step approach of the filament to yarn transformation, which has been successfully developed and implemented in the previously mentioned DFMA code by the Kansas State University. The yarn level composite model allows one to quantify the
effect of the fiber, matrix, interface, and fiber architecture on the composite quasi-static and dynamic properties, which are critical to ballistic performance.

Figure 1. Procedures for integrated modeling of the 3D textile fabrication process, determination of dynamic composite material properties, and composite armor ballistic performance.

Figure 2. The finite element model creation process from the layout of the fabric geometry, through the creation of the geometry in DFMA, to the transformation into a finite element mesh.
The final step shown in Fig. 2 is to use a commercial FE preprocessor to convert the yarn-based micro-geometry model into a finite element model consisting of fabric yarns surrounded by a matrix phase, with an interfacial layer in between. The model was created by initially meshing the yarn-based micro-geometry model using 8-node brick elements with adjustments preventing any initial penetration from fiber to fiber. It is also important to note the node numbering scheme used in the pre-processor to account for the orthogonality of the fiber tow. In this scheme each node was numbered in such a manner that the vector from the first local node in the element to the second local node in the element coincided with the 1-direction of the fiber-tow. Fig. 4 shows an illustration of the node numbering scheme as well as the vector pointing in the 1-direction in a typical fiber tow. At this point a bounding box was created for the matrix phase and a Boolean operation was used to remove the volume of the fiber tows from the bounding box. The volume of the matrix was then meshed using 4-node tetra-elements. Finally, the two phases were combined with a tied interface to form the final composite geometry. Figs. 5 and 6 present efforts to verify the model’s ability to accurately create a woven geometry in comparison to actual composite weaves. It is important to note that the models were created without prior knowledge of the actual weave geometry. It is seen from Figs 5 and 6 that good correlation between the predicted and measured yarn deformation has been achieved.

![Step1](image1.png) ![Step2](image2.png)

Figure 3. An illustration of the two step process transforming the fiber-filament level model in to a yarn level model, the final shape of the yarn continuum is shown in purple in step 2.

![Schematic](image3.png)

Figure 4. Schematic of the node numbering procedure used to ensure proper directional orthogonality of the fiber tows.
B. Composite Yarn Damage Model

Material models have been successfully developed and implemented within LS-DYNA for modeling the progressive failure behavior of 2D and 3D woven composites. These composite failure models have been used to effectively simulate fiber failure, matrix damage, and delamination behavior under all conditions - opening, closure, and sliding of failure surfaces for composite laminates subjected to ballistic impact. Furthermore, this progressive failure modeling approach is advantageous as it enables one to predict delamination when locations of delamination sites cannot be anticipated in a ballistic composite system.

In this study, the failure of each individual yarn bundle in a 3D composite was governed by the failure initiation criteria and the property degradation models as proposed in references. This progressive failure analysis procedure can properly account for the effects due to fiber breakage and matrix damage in individual yarns within 3D composites with computational simplicity.

In the yarn damage model, three criteria are used for fiber failure modes for each representative yarn bundle; one in tension/shear, one in compression, and one in crush under pressure. They were chosen to be quadratic stress forms similar to those for the unidirectional model. When fiber failure in tension/shear mode was determined within an element, the load carrying capacity of that element was gradually reduced to zero using the continuum damage mechanics (CDM) model. For compressive fiber failure, the bundle was assumed to carry a residual axial load, while the transverse load carrying capacity was reduced to zero. When the fiber compressive failure mode was reached, the axial layer compressive stress was assumed to be reduced to a specified residual value. The axial stress remained constant for continuous compressive loading, while the subsequent unloading curve followed a reduced axial modulus to zero axial stress and strain state. When fiber crush failure occurs at the critical pressure, the material was assumed to fail and carries no load after a softening stage.

Two matrix-related failure modes are also considered. Since matrix failure modes occur without fiber failure, they are assumed to be on planes parallel to fibers. A fixed orthogonal crack model is used for the matrix fracture with the maximum numbers of matrix cracks in a yarn bundle being two. As suggested by Hashin, the first fracture plane is determined such that a function involving the normal and two-shear components $\sigma_n \cdot \tau_{nl} \cdot \tau_{nt}$ acting on

![Figure 5. Validation of DFMA models though comparison with actual 6% orthogonal woven composites. The scale of the images is the same for each comparative set.](image)

![Figure 6. Additional comparisons of DFMA model for validation of 6% orthogonal model (pink and green areas represent predicted yarns).](image)
such a transverse plane reaches a maximum. A second fracture plane is assumed to be perpendicular to the first fracture plane. The second matrix fracture may occur if the above function with the stresses expressed in terms of the second fracture plane orientation reaches the critical value. Crack opening, closing and sliding can take place along the directions of the crack surface normal. For an opening matrix crack, the load carrying capacity normal to the crack plane is reduced to zero, while an elastic normal stress and a sliding shear stress are assumed for closing cracks. Under the crack closure condition, this approach effectively models the crack surface friction behavior generated by the normal stress. This model allows one to effectively simulate the dynamic cracking behavior without the use of the usual time consuming contact surface elements. Typical stress-strain curves of unidirectional S2-glass/Epoxy composite for axial tensile, transverse tensile and in-plane shear loads are shown in Fig. 7 and strain rate sensitive data is presented in Fig. 8 for tensile and compressive loadings.

![Figure 7](image7.png)

Figure 7. Material response of unidirectional S2-glass/Epoxy composites for axial tensile, transverse tensile and in-plane shear loads.

![Figure 8](image8.png)

Figure 8. Material response of unidirectional S2-glass/Epoxy composites for axial tensile and compressive loading over varying strain rates. The green lines represent the characteristic unloading/reloading behavior of the material model.

### III. Results and Discussion

Two model configurations were created using the model creation process outline above; a plain weave configuration along with a 6% orthogonal three dimensional weave pattern.

#### A. Plain weave

A 5x5 plain weave model was created and is shown in Fig. 9. The dimensions of the model are 10.1 mm x 10.1 mm x 0.49 mm consisting of 400,000 elements. The model is loaded in the x-direction for uniaxial tension and compression testing over three loading rates ($10^1$, $10^2$, and $10^3$ /sec), with the results shown in Fig. 10. A non-reflective boundary condition is paced on the edges of the sample to eliminate the stress wave reflection. The
initiation and progression of damage on the longitudinal fiber tows is shown in Fig. 11 for the sample loaded at a strain rate of $10^3$/sec. The figures show that the fiber tows begin to fail at the intersection of the warp and the weft and that initial failure causes stress concentrations that propagate to ultimate failure of the longitudinal tow. Additionally, Fig. 10 illustrates that for tensile loads less than 250 MPa the loading rate does not significantly affect the modulus of the composite, but as the load increases there is a noticeable modulus dependency on loading rate. This behavior is interesting because the modulus of the material model of both the fiber tow and of the matrix are rate independent, therefore there must be an additional mechanism at play causing this increase in modulus. It is proposed that the increased loading rate reduces the mobility of the fiber tows at higher loadings and therefore causes an increase in stiffness with increased loading rate.

![Figure 11](image1.png)

**Figure 11.** The evolution of damage in the warp tows of a plain weave model loaded in tension at a strain rate of $10^3$/sec.

![Figure 10](image2.png)

**Figure 10.** Material response of the plain-weave model over varying strain rates for tensile and compressive loadings.
B. 6% Orthogonal weave

The constituents of a 6% orthogonal weave model, of dimensions 14.0 mm x 6.35 mm x 7.25 mm and 500,000 elements, are shown in Fig. 12. The predicted stress-strain curves for the geometry are shown in Fig. 13 for the composite loaded in tension over three dynamic strain rates. The material response shows an increase in the modulus of the composite almost immediately for an increase in loading rate. This suggests that the confinement and relaxation of the fiber tows plays a major role in the response of the 3D woven composite and that higher loading rates restrict the movement of the z-tows creating a more rate sensitive material response. Fig. 14 shows the initial and final state of the composite model loaded at a strain rate of \(10^3\)/sec. The loading in the sample is highest within the z-yarns along the loading direction, which is also the location of initial failure in the composite. In this model the composite begins to fail almost simultaneously in two locations, the bend in the z-tow as it passes over the transverse fibers and longitudinal tearing of the corresponding z-tow in the adjacent location. This pattern suggests that this location, where the z-tows are feed though the weave, acts as a weak point in the geometry for tensile loading. As failure progresses in the material an additional failure mode is identified as delamination at the interface of the transverse tows and the matrix, but this mode occurs much later in the simulation.

![Figure 12. Finite element model for the 6% orthogonal 3D woven composite.](image)

![Figure 13. Material response of a 6% orthogonal weave composite loaded in tension.](image)
In this study, a materials by design procedure was used to investigate the relationship between 2D and 3D composite microstructures and the macroscopic material properties and progressive failure behavior. To achieve this goal, the first critical step was to establish a procedure to generate 2D and 3D composite FE models which consists of the detailed textile micro-geometry configurations of interest. The proposed procedure allows one to easily generate various FE meshes with a desired micro-geometry in an attempt to achieve an optimized fiber architecture design for a specific application. The model incorporated failure criterion to emulate the initiation and progression of damage in the matrix, yarn, and interface of 2D and 3D woven composites.

The preliminary designs were tested to determine the validity of the method and the results were able to represent mechanisms observed in experimental testing with reasonable accuracy as reported in\textsuperscript{15}. Future work will include the testing of additional weave patterns over varying loads, with additional experimental validation.

The complete composite model, which is computationally expansive, will also be simplified to a computationally efficient layer model by providing the representative volume elements for establishing finite element models\textsuperscript{10-12}. The layer composite model can then be used to perform dynamic simulation of ballistic panels to further optimize designs.

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**References**