Stress analysis of 3D textile composites using high performance computing: new insights and challenges

M Keith Ballard and John D Whitcomb
Aerospace Department, Texas A&M University, College Station, TX 77840, USA

Abstract. A finite element analysis (FEA) framework that leverages high-performance computing (HPC) was used to analyze a non-idealized 2x2 orthogonally woven textile model, which was created using VTMS. Since the geometry was not idealized, simple boundary conditions were applied to a large analysis region and an interior subregion was used for investigating the stresses. The variation of the cross-sectional area was investigated, showing that the area varied by 26% within the tows near the top and bottom of the textile model. However, tows near the middle of the textile experienced very little variation in the cross-sectional area. The locations of severe stresses were investigated for two configurations: uniaxial tension along the binder direction and uniaxial tension transverse to the binder direction. It was shown that transverse tension in the tows perpendicular to the load was the most severe stress for both configurations, but the second most severe stress differed for the two configurations. When the load was aligned with the binders’ paths, the second most severe type of stress was transverse tension and longitudinal shear within the binders near the region where they traversed through the thickness of the textile. However, when the load was perpendicular to the binders’ paths, a severe longitudinal shear stress formed in the wefts.

1. Introduction
Two-dimensional textile composites have been routinely used within the aerospace industry, but three-dimensional textiles have received a much slower adoption due to their challenging characterization and manufacturing. Three-dimensional (3D) textiles use through thickness tows that tie the layers together to offer increased toughness, out-of-plane properties, and impact resistance. Three-dimensional woven composites have been used for some applications, such as blade containment systems and body armor, and they offer the potential for multifunctional applications, such as integrating active cooling, self-healing, or a tunable antenna into the material. [1] [2] [3] [4] However, the complex geometry makes it difficult to create realistic textile models and a valid mesh for finite element analysis (FEA). Additionally, the resulting system of equations can be relatively expensive to solve due to the large number of degrees of freedom required. Consequently, there are relatively few works in the literature on the topic, though some researchers have successfully created models for a unit-cell of a 3D woven composite. [5] [6] [7] In 2012, Drach et. al. used the tool DFMA [8], which is very similar to the one used in this study, to create a non-idealized unit-cell for a 3D textile [5], and that model was later used for a few other studies. [9] In 2017, Ballard et. al. studied a small unit cell of a 3D textile model, characterizing the simulated tow geometry, quantifying the
distribution of stress, and investigating the locations of stress concentrations. [10] [11] However, the textile geometry was thinner than the textiles often used in industry, the tow paths were assumed to be 2D when assigning the material properties in the tows, and the unit-cell was so small that the boundary conditions probably introduced artifacts even in the interior of the model. Some groups have used non-standard FEA models, such as the voxel approach used by Green et. al. [6]

Learning from the shortcomings in Ref. [10] and [11], this paper will consider a more realistic, thicker textile. Orthogonally woven binders cross two wefts before traveling through the thickness, sometimes referred to as a 2x2 orthogonal weave. Tow paths will be 3D instead of 2D, and a local coordinate system will be assigned to each node instead of one coordinate system per element. To avoid boundary condition effects, a much larger analysis region will be considered, and a subset of the region will be used for post-processing to ensure artifacts due to the in-plane boundary conditions are avoided. This paper provides a characterization of the variation of the cross-sectional area of the tows and an investigation of stress concentrations for two load configurations, including an explanation of how load is transferred to cause the concentrations.

This paper is separated into two sections. The first section describes the geometry, mesh, boundary conditions, clipped region used for post-processing, and material properties used for this study. This is followed by the results section, which quantifies the variation of the cross-sectional area in the tows and explores the locations and causes of stress concentrations.

2. Finite Element Model

This section begins with a description of the method used to generate the textile geometry. Next, an overview of the steps used to create a conforming mesh and a description of the resulting mesh is provided. The boundary conditions for the two configurations are given. To avoid boundary effects, the boundary conditions are applied to a larger analysis region, and the analysis region is clipped down to a subregion, which will be used for all discussion in the results section. Finally, the material properties used for each constituent are presented.

2.1. Textile Geometry

A software tool called VTMS was used to create the geometry for a 3D textile. The Air Force Research Lab (AFRL) developed VTMS for modeling the effects of processing on the tow geometry, allowing the generation of realistic textile models. It models the effects of processing through the use of “digital chains”, which consist of rigid spheres along an elastic wire. Ideally, a digital chain should be used for each fiber within the tow, but this is currently computationally prohibitive. Initially, the digital chains have a lot of space between them. The displacements at the ends of the digital chains are specified to be zero, and a contact analysis is used to solve for the final configuration. During the contact analysis, a tension is specified within the digital chains and a pair of rigid planes is used to compress the top and bottom of the model. The contact analysis prevents overlap between the rigid spheres of the digital chains, and tension in the chains encourages them to move towards the midplane. It is useful to begin with one digital chain per a tow until the unrealistic space between the tows is removed, and afterwards, the single digital chains are replaced with more digital chains. Each single digital chain was replaced with ten digital chains for this model. With multiple digital chains per a tow, the cross-section of the tows can deform during the contact analyses. After compaction and the final configuration is reached, cross-sectional profiles are created along each tow path by fitting a closed spline around the bundle of digital chains that define the tow cross-section for each sample point along the tow path. Typically, between two and five hundred cross-sectional profiles are sampled for each tow. Once a solid geometry has been created for each tow, interpretations between the tows are
removed by adjusting the geometry of each tow. The algorithm used in VTMS to remove interpenetrations is not precise enough to allow the creation of a conforming, non-intersecting volume mesh for each tow. Consequently, the cross-sections for each tow are shrunk towards the centroid by a small amount, resulting in some matrix material between each tow. For the final steps in VTMS, the surface geometry of each tow is discretized and clipped to a smaller region to avoid the spurious effects near the edges of the initial model.

Figure 1a shows the resulting model with the matrix added, along with the dimensions of the model. The model consists of four layers of warps and five layers of wefts through the thickness, and the binders are in a 2x2 pattern where they cross two wefts at the top or bottom of the weave before traversing through the thickness. Figure 1b shows the tow architecture more clearly by removing the matrix and highlights the
variation of cross-section shapes within the tows. Since VTMS uses a rigid mold to compact the textile geometry, the outermost tows experience more deformation than the tows nearest the midplane, which is shown in Figure 1b. The extreme deformation of the outermost tows is reduced by compacting one layer at a time, but the outermost tows will still experience more deformation than the interior tows when the binders are compacted. Creating realistic 3D textile models remains an important challenge for the research community. Tools like VTMS and a very similar software called DFMA provide a method for producing non-idealized textile geometries, which is a step in the right direction, but significant work remains to ensure that the geometries closely resemble physical specimens.

2.2. Mesh

This work uses a standard FEA formulation, which requires a conforming mesh. The VTMS software includes meshing for the independent mesh method [12], but the resulting mesh is not usable herein because it is nonconforming. Instead, an in-house tool was used to create refined surface meshes of the tow geometries. The surface meshes were then used to create volume meshes of the tows and matrix using quadratic tetrahedrals, leveraging a general tetrahedral meshing library called TetGen [13]. Figure 2 illustrates the typical mesh refinement. Tows generally have 5 to 10 quadratic tetrahedrals through the thickness of the tows. A higher mesh refinement exists near binder tows. The final mesh used for this paper consists of 20 million nodes and 15 million quadratic tetrahedrals. It should be noted that the surface geometry that is taken from VTMS is faceted, resulting in unrealistic sharp corners between facets. Ideally, the faceted geometry should be smoothed to avoid unrealistic stress concentrations near sharp corners, but this is not done in this study. At the level of mesh refinement used in this study, it is not clear whether the faceted geometry has a significant effect.

The in-house meshing tool uses a cubic spline fit of the tow centroids to define each tow path. The material coordinate system is determined at each node within a tow mesh by finding the closest point on the spline of the tow path and using the tangent vector of the spline as the fiber direction, which defines the local x-axis. The local y-axis is assigned to be parallel to the cross product between the global z-axis and the tangent vector. The final local z-axis is defined by the cross product of the local x and y-axes, which defines a right-handed coordinate system.

Figure 2. Illustration of mesh refinement
2.3. Boundary Conditions and Clipped Analysis Region

Ideally, periodic boundary conditions would be applied to a textile unit-cell, but the geometry from VTMS is not periodic since it creates a model by virtually simulating textile processing. Consequently, a larger section of the textile is modeled, simple boundary conditions are applied to the larger analysis region, and a subregion is used for post-processing to reduce artifacts due to the boundary conditions.

Three faces of the full analysis region (the \(x = 0\), \(y = 0\), and \(z = 0\) planes) are assumed to be planes of symmetry. Refer to the coordinate system in Figure 1a. This results in the following boundary conditions: \(u(0, y, z) = 0\), \(v(x, 0, z) = 0\), and \(w(x, y, 0) = 0\). In addition to these boundary conditions, two loading configurations are considered: uniaxial tension along the global \(x\)-axis and uniaxial tension along the global \(y\)-axis. The loading consists of specified displacements to result in a 1% volume average strain. Specifically, this requires \(u(13.4\ mm, y, z) = 0.134\ mm\) for tension along the \(x\)-axis and \(v(x, y = 11.4\ mm, z) = 0.114\ mm\) for tension along the \(y\)-axis. All other boundaries are traction free.

As mentioned before, the boundary conditions are applied to the full analysis region, and the analysis region is clipped for post-processing to reduce any artifacts near the boundaries that emerge from non-periodic boundary conditions. Figure 3 shows the full analysis region and the subset of the region used for post-processing. The clipped region used for post-processing is only approximately a full unit-cell, since the textile geometry is non-periodic. The in-plane boundaries of the clipped analysis region are not planar since the tetrahedral elements are not cut by the clipping process. Any element with a node within the clipped analysis region is kept, while all others are removed, resulting in a rough surface on each clip plane, which can be observed in Figure 3b or Figure 3c.

**Figure 3.** Illustration of the full analysis region and clipped region used for post-processing.
2.4. Material Properties

For this study, the tows are assumed to consist of 60% IM7 graphite fiber and 40% 5220-4 epoxy by volume. An ensemble of random fiber/matrix models was used to predict the effective tow properties, similar to the method described in Ref. [14]. The material properties for the tows and neat matrix are shown in Table 1. Since this is an early study into the stress distributions of 3D textile models, linear elasticity was assumed.

| Table 1. Material properties          |
|---------------------------------------|
| **IM7/5220-4 Tows**                  |
| $E_1$ (GPa)                           | 167  |
| $E_2$ (GPa)                           | 10.3 |
| $G_{12}$ (GPa)                        | 5.42 |
| $G_{23}$ (GPa)                        | 3.32 |
| $\nu_{12}$                            | 0.31 |
| $\nu_{23}$                            | 0.54 |
| **5220-4 Epoxy Matrix**              |
| $E$ (GPa)                             | 3.45 |
| $G$ (GPa)                             | 1.28 |
| $\nu$                                 | 0.35 |

3. Results

The results of this paper are organized into two sections. The first section characterizes the tow architecture, and the second section investigates the stress distributions within the tows.

3.1. Characterization of Tow Architecture

Since the textile geometry is the result of simulated processing, the cross-section of the tows can vary along the tow paths due to a variety of reasons. During compaction, the cross-sectional area is likely to be reduced where tows contact other tows. Additionally, the shape of the tows can vary significantly when it changes direction, such as when the binder begins or ends traveling through the thickness of the textile. Characterizing the variation of the cross-sections of the tows is a first step toward understanding how closely the model resembles actual specimens. This section quantifies the variation of cross-sectional area and explains how aspects of VTMS’s method for creating textile models led to the variations.

For the model considered in this paper, adjacent binders have a different phase of undulation through the textile, but every fourth binder has the same phase. Every other binder will traverse through the thickness of the textile at the same gap between weft tows, and so a pair of such binders is more likely to have similar cross-sectional areas. Figure 4 shows the variation of the cross-sectional area of the first and third binder, which are shaded in the figure as green and purple and labeled 1 and 3. The cross-sectional area is maximum where the binders are midway through the thickness of the textile, since these regions are not affected significantly by compaction, resulting in the area at the midpoint through the thickness remaining almost unchanged throughout the compaction process. The minimum occurs where the binders transition to and from traveling through the thickness. The low cross-sectional area at these points are due to several factors, such as the lower radius of curvature and the tension in the binders causing the binders to strongly contact neighboring wefts. Additionally, it was observed that digital chains tend to pass through each other in these regions, resulting in significant tow interpenetrations. It is unclear which factors are most significant, but the cross-sectional area decreases by 19% to 24% as the binders transition into traveling through the thickness, such as at point A in Figure 4. Where the binders are on the top or bottom of the textile, the cross-sectional area varies by at most 18%. It is unclear if this much variation is realistic or merely an artifact of the method used by VTMS to create the textile geometry.
Figure 4. Variation of the cross-sectional area in the first and third binders

Figure 5 shows the variation of the cross-sectional area in the warp tows. Figure 5a shows that the cross-sectional area for the inner two layers of warps (green) remains relatively constant, varying at most by 4.5%. However, Figure 5b shows that the warps on the top and bottom of the textile experience significant changes in cross-sectional area. There are two types of variation of interest. One type of variation is that the cross-sectional area of a single tow changes along the tow path, which for the outer layer of warps is at most 11%. Another type of variation is that the cross-sectional area varies between tows in the same layer, which is at most 15% for the model presented in this paper. Both types of variations will exist in actual specimens, but comparisons to MicroCT scans would be needed to quantify the accuracy of the model geometry. However, these results do show that the cross-sectional area of tows in a model created by VTMS largely depend on the distance from the boundaries where the compaction planes contact the model. The deformation due to the rigid planes at the top and bottom boundaries does not cause significant deformation well into the interior of the model. Tows near the boundaries will be highly deformed, while tows in the interior will experience...
little deformation. The variation of the cross-sectional area in the wefts were not shown for conciseness, but they follow the same trend. The outermost layers varied by up to 26%, while the innermost layer varied by less than 2%.

Figure 5. Variation of the cross-sectional area in the warps
3.2. Analysis of a 3D Textile Subjected to Uniaxial Tension

The 3D textile model was subjected to two types of load: uniaxial tension along the global x-axis and uniaxial tension along the global y-axis. This paper assumes linear elasticity, so the behavior of progressive damage cannot be understood from these results, but for each load configuration, this section aims to investigate the locations of stress concentrations and the local load transfer that caused the concentrations.

Stresses in the global coordinate system are denoted as $\sigma_{ij}$, while stresses in the local coordinate system are denoted by a prime, $\sigma'_{ij}$. To quantify the severity of stresses within the tows, components of stress in the local coordinate system are normalized by a nominal strength and denoted by a hat, $\hat{\sigma}'_{ij}$. Ideally, the strengths would be based on a series of experiments or microscale damage analyses. However, for this paper, the strengths will be assumed to be the same as the tows tested in Ref. [6], which have similar elastic properties to those used herein.

3.2.1 Tension Along X-Axis. Figure 6 shows the three most severe normalized stresses within the clipped analysis region for an applied volume average strain along the global x-axis, $\langle \varepsilon_{xx} \rangle$, of 1%. The stresses shown are in the local coordinate system, and each stress component is normalized by the respective strength, which provides a measure of the severity of each stress component. Overall, Figure 6 shows that wefts and binders experience the most severe stresses.

The binders experience severe $\sigma'_{zz}$ and $\sigma'_{zz}$ components of stress, as shown in Figure 6b and Figure 6c respectively. The severe $\sigma'_{zz}$ occurs where the binders travel through the thickness of the textile model, as shown in Figure 6b. To show the locations of stress concentrations more clearly, Figure 7 shows $\hat{\sigma}'_{zz}$ within an x-z slice of one of the binders. In this region, the local z-axis almost aligns with the global x-axis, which is the direction of the load, refer to Figure 7b. Additionally, there are no wefts in the region where the binders travel through the thickness of the textile. Consequently, the binders take on much of the load via tension along the local z-axis. The peak stresses occur where wefts are nearby to transfer the load to the binders. This component of stress will likely cause transverse matrix cracking within the binders.
Figure 6. Contours of three most severe stress components in the local coordinate system normalized by the respective strength for uniaxial tension along the global x-axis
In addition to the severe transverse tension, the binders experience a severe shear stress, $\sigma'_{xz}$, where they begin and finish traveling through the thickness of the textile, as shown in Figure 6c. The shear stress develops to maintain equilibrium as the binders shift between carrying a significant amount of load at the top and bottom of the textile, where the fibers of the binders are aligned with the load direction, to carrying much less load as they travel through the thickness of the textile.

Though the binders experience severe stresses, the wefts experience the most severe stress, namely $\sigma'_{yy}$, within the textile, as shown in Figure 6a. For the wefts, the local y-axis is closely aligned with the global x-axis, which is the direction of the applied load for this configuration, so it is expected that the transverse tension in the wefts will be severe. However, the severity of the transverse tension varies dramatically depending on the location within the wefts. Figure 8 shows the local and global stress components of interest for an x-z cross-section centered on a binder tow, which is illustrated in Figure 7a. Figure 8a shows the $\sigma'_{yy}$ contours in the wefts and binder in the x-z cross-section. In most locations, $\sigma'_{yy}$ remains between 2 and 3. At some points when the wefts come close to a binder, $\sigma'_{yy}$ reaches values near 4.5, such as point A in Figure 8a, but at other points near a weft tow, no stress concentration occurs, such as point B in Figure 8a. The common factor for areas of elevated stress is a sharp cross-sectional shape of the weft. When the cross-section is similar to a rectangle with rounded corners, there is no significant stress concentration, but when the cross-section comes to sharper point, a significant stress concentration occurs. The sensitivity of stress concentrations to the tow cross-sectional shape emphasizes the importance of creating textile models with realistic tow geometries.

Figure 7. $\sigma'_{zz}$ contours for an x-z cross-section of a selected binder illustrating locations of severe $\sigma'_{zz}$ in binders.
There is one situation where the tow shape is less prone to cause a stress concentration for this configuration: where a binder crosses over a weft tow. In this region, $\delta_{yy}'$ in the weft drops to about 0, such as point C in Figure 8a. The drop in transverse tension is due to a compressive $\sigma_{xx}$ (global) in the region where a binder crosses the wefts at the top or bottom of the textile, such as region D highlighted in Figure 8b. The compressive stress forms as load is transferred to or from the binder via shear, since the binder is orders of magnitude stiffer in the global $x$-direction than the surrounding material at the top and bottom.

![Diagram](image)

**Figure 8.** An $x$-$z$ cross-section illustrating locations of severe local transverse tension in wefts

### 3.2.2 Tension Along $Y$-Axis

Figure 9 shows three most severe normalized stresses within the clipped analysis region for an applied volume average strain along the global $y$-axis, $\langle \varepsilon_{yy} \rangle$, of 1%. Again, the normalized stresses shown are in the local coordinate system. Overall, Figure 9 shows that the warps and binders experience severe transverse tension ($\delta_{yy}'$), while the wefts experience severe longitudinal shear ($\delta_{xy}'$ and $\delta_{xz}'$).

The most severe stress in the textile is $\delta_{yy}'$ in the binders and warps. For both types of tows, the local $y$-axis is closely aligned with the global $y$-axis, which is the direction of the load for this configuration. To illustrate where the peak stresses occur in the textile, Figure 10 shows $\delta_{yy}'$ for one binder and row of warp tows, along with the local coordinate system for a point in the binder. The figure shows that the stress concentrations form where warps and binders come closest, such as point A in Figure 10. Additionally, stress concentrations form where the binder begins or ends traveling through the thickness of the textile, such as points B in Figure 10.
Figure 9. Contours of each stress component in the local coordinate system normalized by the respective strength for the case of uniaxial tension along the global y-axis
In summary, the transverse normal stress $\sigma_{yy}'$ was the most severe component for both configurations. In both cases, the peak $\sigma_{yy}'$ occurred within the tows that are perpendicular to the load. However, when the load is along the global x-axis, the stress concentrations only form within the wefts, but when the load is along the y-axis, the stress concentrations form within the binders and warps. Additionally, the stress concentrations are more severe for the case of tension along the x-axis.

![Figure 10. $\sigma_{yy}'$ for a selected binder and row of warp tows](image)

The second most severe type of stress in the textile is the longitudinal shear stresses, $\sigma_{xy}'$ and $\sigma_{xz}'$, within the wefts. To more clearly show the locations of severe shear stress, Figure 11 shows the magnitude of the normalized longitudinal shear stress, $\sigma_{s}' = (\sigma_{xy}'^2 + \sigma_{xz}'^2)^{1/2}$, for the volume of wefts with a value of $\sigma_{s}' > 1.2$. The entire weft tows are shown semi-transparently for context of where stress concentrations occur. Figure 11 shows that the severe shear stresses in the wefts occur in the top and bottom layers of tows and near locations where binders cross the wefts. It should be noted that the stress concentrations do not occur uniformly throughout the model due to variations in the textile geometry and mesh refinement.

In summary, the second most severe stress for both configurations was the longitudinal shear stress, but the locations of severe shear stress differed for the two types of loads. When the load was along the global x-axis, the severe shear stresses developed in the binders, but when the load was along the global y-axis, the severe shear stresses developed in the wefts. This indicates that the progression of damage might depend on the direction of load relative to the binders’ paths.
Figure 11. Magnitude of normalized longitudinal shear stress, $\sigma_z^x = (\sigma_{xy}^2 + \sigma_{xz}^2)^{1/2}$, for the volume of wefts with a value of $\sigma_z^x > 1.2$ (entire weft surfaces are shown as semi-transparent)

4. Conclusions
An in-house FEA code that leverages high-performance computing was used to analyze a large non-idealized 3D textile model with a 2x2 orthogonal weave created using VTMS and an in-house meshing tool. Due to the complexity of 3D textiles, the geometry of the model was characterized by quantifying the variation in the cross-sectional area along the tow paths. It was shown that the cross-sectional area in tows near the top and bottom boundary of the model exhibited large amounts of variation up to 26%. On the other hand, tows near the middle of the weave exhibit relatively little variation. In reality, tows experience some amount of variation in the cross-sections, but about the same number of fibers exist for any slice, which causes the fiber volume fraction to vary along the tow path. The range of variation of cross-sectional area in the model indicates that the variation of fiber volume fraction should be accounted for and could significantly affect the locations of stress concentrations. It will be important for future works to quantify the variation of the cross-sectional shape and compare the variation of tow architecture to actual specimens.
The locations of severe stresses were investigated for two configurations: uniaxial tension along the global x-axis and uniaxial tension along the global y-axis. Under tension in the x-direction, the wefts experienced the most severe stress in the textile, exhibiting a high transverse tension along the local y-axis, $\sigma'_{yy}$. The severe $\sigma'_{yy}$ will likely lead to initial matrix cracking in the wefts. It is important to note that the largest $\sigma'_{yy}$ in the wefts developed when wefts came close to a binder and the cross-sectional shape of the weft came to a sharp corner. The sensitivity of the stress concentrations to the tow shape highlight the need to create textile models with realistic tow architectures if the progression of damage is to be accurately predicted. Additionally, the binders exhibited a severe transverse tension and longitudinal shear, namely $\sigma'_{lz}$ and $\sigma'_{lz}$, near where they traverse through the thickness of the textile. Unless matrix cracking in the wefts relieves the stress concentrations in the binders, the binders are likely to experience matrix cracking and longitudinal shear failure early in the progression of damage within the textile.

For the case of uniaxial tension along the global y-axis, transverse tension, $\sigma'_{yy}$ in the warps and binders was the most severe type of stress in the textile. This is very similar to the previous configuration, though the severe stress is in different types of tows. Similarly, transverse matrix cracking is likely to occur in the binders and warps initially. However, the second most severe type of stress is very different from the previous configuration. When the load is transverse to the binders, a severe longitudinal shear stress develops in the wefts. Though the initial type of damage expected matches for the tension along the x- and y-directions, namely transverse matrix cracking, the next most severe types of stress are fundamentally different between the two cases due to the presence of binders. Without the binders, the severe shear stress is not expected to develop, showcasing the need for understanding what role binders play in distributing load within complex 3D textile geometries.

Creating realistic 3D textile models remains a challenge for the community. This paper took a step forward by using a large non-idealized model, a refined mesh that required the use of high-performance computing, clipping the analysis region to avoid boundary effects, and investigating the locations of stress concentrations with more detail. However, it was also shown that the shape of tows can be important, the variation of the fiber volume fraction should be accounted for, and understanding the role of the binders requires further study.

Acknowledgements
This work was supported by the Department of Defense (DoD) through the National Defense Science & Engineering Graduate Fellowship (NDSEG) Program. In addition, the authors acknowledge the Texas A&M Supercomputing Facility (http://sc.tamu.edu/) for providing computing resources used in conducting the research reported in this paper.

References

[1] A. Esser-Kahn, P. Thakre, H. Dong, J. Patrick, V. Vlasko-Vlasov, N. Sottos, J. Moore and S. White, "Three-Dimensional Microvascular Fiber-Reinforced Composites," Advanced Materials, vol. 23, p. 3654–3658, 2011.

[2] R. Gibson, "A review of recent research on mechanics of multifunctional composite materials and structures," Composite Structures, vol. 92, pp. 2793-2810, 2010.
[3] D. Hartl, G. Huff, H. Pan, L. Smith, R. Bradford, G. Frank and J. Baur, "Analysis and Characterization of Structurally Embedded Vascular Antennas Using Liquid Metals," in SPIE Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems, Las Vegas, NV, 2016.

[4] S. Rawal, D. Barnett and D. Martin, "Thermal Management for Multifunctional Structures," IEEE Transactions on Advanced Packaging, vol. 22, no. 3, pp. 379-383, 1999.

[5] A. Drach, B. Drach and I. Tsukrov, "Processing of fiber architecture data for finite element modeling of 3D woven composites," Advances in Engineering Software, vol. 72, p. 18–27, 2014.

[6] S. D. Green, M. Y. Matveev, A. C. Long, D. Ivanov and S. R. Hallett, "Mechanical modelling of 3D woven composites considering realistic unit cell geometry," Composite Structures, vol. 118, pp. 284-293, 2014.

[7] S. Soghrati, A. R. Najafi, J. H. Lin, K. M. Hughes, S. R. White, N. R. Sottos and P. H. Geubelle, "Computational analysis of actively-cooled 3D woven microvascular composites using a stabilized interface-enriched generalized finite element method," International Journal of Heat and Mass Transfer, vol. 65, pp. 153-164, 2013.

[8] G. Zhou, X. Sun and Y. Wang, "Multi-chain digital analysis in textile," Journal of Composites Science and Technology, vol. 64, pp. 239-244, 2003.

[9] I. Tsukrov, B. Drach, H. Bayraktar and J. Goering, "Modeling of Cure-Induced Residual Stresses in 3D Woven Composites of Different Reinforcement Architectures," Key Engineering Materials, Vols. 577-578, pp. 253-256, 2014.

[10] M. K. Ballard, J. S. McQuien and J. D. Whitcomb, "Analysis of three-dimensional woven composites," in 21st International Conference on Composite Materials, Xi'an, 2017.

[11] M. K. Ballard and J. D. Whitcomb, "Prediction of Tow Architecture and Stress Distributions for a 3D Woven Composite," in American Society of Composites, West Lafayette, Indiana, 2017.

[12] E. V. Iarve, D. H. Mollenhauer, E. G. Zhou, T. Breitzman and T. J. Whitney, "Independent mesh method-based prediction of local and volume average fields in textile composites," Composites Part A: Applied Science and Manufacturing, vol. 40, no. 12, pp. 1880-1890, 2009.

[13] H. Si, "TetGen, a Delaunay-Based Quality Tetrahedral Mesh Generator," ACM Transactions on Mathematical Software, vol. 41, no. 2, 2015.

[14] M. K. Ballard, W. R. McLendon and J. D. Whitcomb, "The influence of microstructure randomness on prediction of fiber properties in composites," Journal of Composite Materials, vol. 48, no. 29, pp. 3605-3620, 2014.