A High-Fidelity Progressive Damage Model for 3D Textiles with Microvascular Channels

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# Introduction

The design of high-performance, composite materials is crucial to creating transformative capabilities in the aerospace industry. A computational framework that allows the design from the microscale, where fibers and matrix are modelled discretely, to achieve performance at larger scales would expedite the discovery, design and insertion of entirely new materials. Though industry has been increasingly using composite material within aerospace applications, there exists numerous opportunities for novel, transformative technologies through the design of composite materials from the microscale, rather than design from the mesoscale, where homogenized laminae or tows are modelled. Composites with microvascular networks could allow self-healing by transporting reacting materials to cracks to form a structural resin or active cooling by pumping a coolant through the material. [1] [2] [3] Microvascular networks also have the potential to create embedded, tunable antennas within a structure [4], increasing the response of shape memory polymer structures [5]. Manipulating fluids inside microvascular channels via microscale valves, mixing chambers, and other components have many potential applications, such as chemical synthesis, and has been developed into a distinct field, microfluidics. [6] Embedded sensing fibers within a composite offers the ability to sense deformation and damage in real-time. [1] [2] Shape memory materials have the potential of constituting morphing structures without the need of discrete actuators, saving cost and weight and creating a possibility for many new technologies. [2] [3] Each of these applications have been proposed and studied to some extent by researchers, but the technologies are still far from being integrated into commercial aerospace products, aside from a few research collaborations. Additionally, these technologies often rely on more complex composite designs, such as 2D and 3D woven textile composites, than the laminates composed of unidirectional laminae typically used in the industry.

An example of a possible multifunctional structure that could simplify the design of a system can be found in satellites and space vehicles. As electronics continue to grow in computational power and more processing units and sensors are incorporated, the thermal management system is becoming more important. In addition to the thermal management, a structure is needed to protect the electronics from electromagnetic interference (EMI) or mechanical impact. Advanced composites with microvascular channels have the potential to provide all of these functions. Electronics can be directly bonded onto structures with highly thermally conductive or actively cooled structures, allowing heat to be transferred directly to radiating panels. [7] [8] [9] Additionally, continuous carbon fiber woven composites provide useful EMI shielding properties [2] [10] [11], and 3D textiles can provide excellent out of plane properties, especially damage tolerance, compared to 2D composites. [12] These properties and concepts create the possibility for a multifunctional composite to serve as thermal management, EMI shielding, and structural protection system for electronics in space.

To design such complex materials will require a combination of experimental characterization and a robust multiphysics/multiscale computational framework, which should provide useful design insights to guide the experiments and optimal design of the material. Most importantly, the design tradeoffs between the functional performance and mechanical performance need to be well-understood. Functional constituents can cause damage to initiate at an earlier load compared to a non-functional composite and can significantly change the way damage progresses in the material. Understanding the effect of functional constituents on the mechanical performance and the progression of damage is key for the design of multifunctional composite structures.

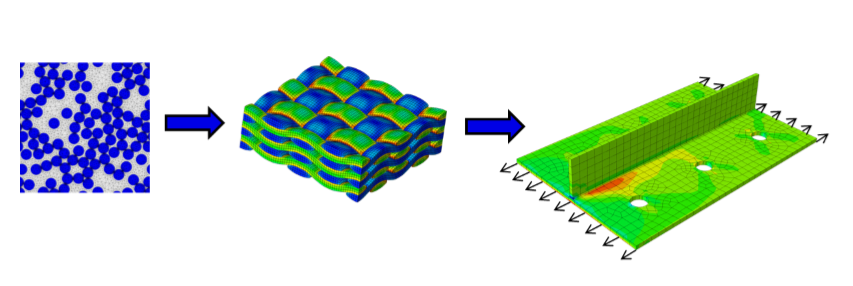
To predict the effect of microscale multifunctional constituents on the response of a large scale component, a computational framework capable of predicting the response of the material across various scales is needed. The extensive, robust field of finite element methods (FEM) offers the necessary building blocks for such a computational framework. Finite element methods have been in development for many decades and have become a reliable and useful design tool for engineers and researchers. There have been many fields of FEA that focus on describing a material at multiple scales, including multiscale finite element methods (MsFEM), which includes several subsets of methods aimed at linking the solution across spatial or temporal scales when the scales and domains are known a priori. [13] [14] When multiscale finite elements are used in parametric studies or the optimization of a material, a hierarchical approach is typically adopted, which relies on the homogenization of elastic properties. The homogenization techniques provide significant computational efficiency but are only valid when the material does not experience localized phenomena (such as cracks, shear bands, etc.) and maintains a clear separation of scales. If the design of a structure requires an understanding of localized microscale phenomena or an engineer wants to know if a measured defect at some scale will be catastrophic to the larger structure, then homogenization techniques are inadequate, and it is for this type of problem that the field of multiscale finite elements was developed. MsFEM has been extended to be adaptive and model the material at the necessary scales and refinement based on error estimates, which is known as adaptive finite element methods. [15] [16] [17] In the design of multifunctional materials, the combination of multiscale methods with a framework for parametric studies or optimization will provide a greatly needed understanding of the effect of integrating multifunctional constituents into advanced composites.

Within a multiscale framework, a model for the progression of damage at each scale is needed if the effect of multifunctional constituents on the failure of a component is to be understood. At the microscale, researchers have proposed numerous models to predict the progressive of damage. Some popular approaches include the use of continuum damage elements [18], which models the effect of a damage parameter on the response of a material, cohesive zones placed along a predetermined potential crack path [19], which models the discrete crack explicitly, a plasticity model for matrix damage combined with cohesive zone elements for interfacial debonding [20] , and mesh independent methods[21][22], which allow the crack to grow along an arbitrary path. At the mesoscale, where a laminate or textile is considered, damage from the microscale can be accounted for through the use of a reduced order model or modelled explicitly through a concurrent model, in which the behavior of a critical area of the mesoscale domain is modelled concurrently through a detailed microscale analysis. [23] [24] Additionally, there are new damage modes introduced at the mesoscale, such as delamination of tows or laminae, and these can be accounted for through a cohesive zone model, for example. The same strategy used to bridge the microscale to mesoscale can be used to predict the macroscale material behavior in the presence of mesoscale damage. Though there is considerable effort in the field for linking molecular dynamic (MD) analyses to microscale analyses, the smallest scale considered in this work will be the microscale. The emerging multiscale strategies combined with a damage model for each scale have the potential to significantly change how engineers approach the design of structures by providing an understanding of how much damage can be allowed before a component needs to be replaced, which component failures would be catastrophic, what damage modes the component will experience during failure, and ultimately how to design better materials.

This dissertation aims to apply multiscale finite element methods to predict the effect of incorporating functional constituents into fiber reinforced composites. In particular, the design of a 3D woven textile with microvascular channels for active cooling will be considered. Several types of microvascular networks will be studied, including in-plane straight channels between layers and channels inserted via sacrificial tows (varying the weave, channel size, channel orientation, and channel pattern). Figure 1a shows an illustration of a composite manufactured with channels between two woven layers of a textile using tubes and sacrificial fibers. [25] Figure 1b shows a 3D orthogonally woven textile composite similar to the vascular composite studied in [26], which considered sinusoidal vascular channels in the composite. Some work has been published exploring the effect of microvascular channels on the overall elastic properties of 3D textiles, but no detailed models have been developed for predicting the effect on the failure behavior of 3D textiles, which this work will consider. To model the progression of damage, a plasticity model will account for yielding in the epoxy matrix, a cohesive zone formulation combined with either standard FEA or the augmented finite element method (AFEM), which uses overlapping elements to describe a discontinuity. will govern the opening of cracks in the matrix and along fiber/matrix interfaces. A multiscale finite element framework will then be combined with these strategies to predict the progression of damage across the microscale, mesoscale, and macroscale. Finally, an optimization algorithm will use the predictions from the multiscale finite element framework to find an optimal design for multifunctional component. An overview of the proposed framework is illustrated in Figure 2. The challenge of this problem lies in accounting for localization phenomena across multiple scales and the numerical implementation’s efficiency and scalability.

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| a) Vascular channels inserted between weave layers in a textile composite (Figure 3 from [25]) | b) An idealized 3D orthogonal textile similar to the one considered in Ref. [26], where channels can be inserted via sacrificial tows |

Figure 1. Two possible vascular channel types



Microscale model:

* Fibers, matrix, and microscale vascular channels
* Plasticity model in matrix
* Cohesive zones along fiber-matrix interface and placed in matrix adaptively for cracks

Mesoscale model

* Tows, neat matrix, and tow-scale vascular channels (either along tow path or between layers)
* Cohesive zones to model matrix-tow debonding

Macroscale model

* Engineering component
* Overall functional and mechanical performance predicted

Information passed via hierarchical model, reduced order model, or concurrent model

**Multiscale finite element framework**

**Optimization framework**

Define geometry of vascular channel design (microscale volume fraction, location at mesoscale, size of channels, etc.)

Calculate performance index from macroscale model

Iterate: change design to improve the performance index

Stop when maximum iterations are reached or optimal design if found

Figure 2. Overview of framework for the optimization of multifunctional material across scales

The novel contributions of this work to the field can be separated into two types. First, there will be contributions in the field of multifunctional material optimization for advanced composites, including:

* A high-fidelity finite element model, which will involve a new high-performance computing (HPC) finite element framework, for modelling progressive damage in 3D textile composites
* Reduced order models for the tow/lamina scale and textile/laminate scale guided by the results of the high-fidelity finite element model, which can be used as a predictor within a multiscale optimization scheme or a design tool for engineers
* An understanding of how functional microvascular channels affects the mechanical performance across scales, especially the effect on the initiation and growth of damage

Second, advances in the field of computation, optimization, and multiscale finite elements will be established, including:

* Methods and algorithms for adaptive multiscale analysis of progressive damage in materials that are suitable for high-performance computing (HPC) frameworks, which is a field largely ignored by MsFEA and optimization communities
* Strategies to visualize large, distributed multiscale data, allowing the exploration of the results from these analyses to gain useful insights
* A suite of extensible computational tools for other researchers and hopefully engineers to build upon to solve even more challenging problems

The scope of the proposed work is extensive, involving several key challenges, high-performance code developments, and the combination of several fields of science and engineering. A brief literature review of the relevant fields and current state of the art is given in the next section. The anticipated challenges and potential solutions are discussed in a following section, including a description of the algorithms, existing computational tools, and methods that might be used. Finally, the research plan with a timeline of development and publications are provided.

# Preliminary Literature Review

The concept of manufacturing composites with vascular channels began with self-healing composites. [27] In the early 1990’s, Dry had proposed embedding healing agents in a composite via hollow glass tubes. [28] [29] Following that work, several other researchers evaluated the use of hollow tubes to transport healing agents inside a composite. [30] [31] [32] White et. al. demonstrated the positional possible to heal large volumes of material via species transported through embedded straight vascular channels. [33] Eventually, researchers studied 3D vascular networks embedded in polymeric solids for self-healing. [34] [35] Vascular channels used for self-healing is still receiving some attention in the literature. Recently, Patrick et. al. showed that sacrificial orthogonal tows within a 3D woven composite could be filled with parts of healing agents that react upon mixing, and when delamination between weave layers occurs, the orthogonal channels release the agents, creating a self-healing functionality. [36] More detailed reviews of vascular channels used for self-healing can be found in Ref. [27] and [37]. Within the self-healing community, researchers began considering using the hollow tubes or channels for sensing or active cooling. [34] Many of the challenges studied by researchers for self-healing composites are directly applicable to other functional vascular composites.

During mid-2000’s, a considerable number of papers began to focus on using microvascular channels in composites for active cooling, with much of the work originating at the Air Force Research Laboratory (AFRL) or University of Illinois Urbana-Champaign (UIUC). In one of the early works, Aragón et. al. used a genetic optimization approach to design 2D vascular channel paths in a polymeric solid. The optimization sought to minimize the flow resistance and minimize the volume fraction of channels in the solid, which required a design tradeoff since the two objectives cannot be accomplished at once. The model assumed Poiseuille flow in the channels and used simple models for predicting the thermal response in the solid, but it was an early attempt to use evolutionary algorithms to design vascular channels. [38] The optimization technique was later extended to design a 3D channel network via an evolutionary algorithm. [39] Nguyen and Orifici developed a finite element model for predicting the ultimate strength and failure modes for [0/90]n laminates with embedded glass tube channels. A progressive continuum damage model was used within unidirectional plies, which were modelled as homogeneous material, and cohesive zones were inserted between plies to model delamination. The analyses predicted knockdown parameters for each of the mechanical properties for tensile loads along and transverse to the channel directions. Since the channels were quite large and not embedded within the unidirectional plies, the main effect of the channels was introducing a waviness in the composite. When the load was aligned with the channels, the waviness did not noticeably affect the mechanical response, but when the load was aligned transverse to the channels, the waviness led to a reduction in the ultimate strength of the composite. [40] Hartl et. al. used a continuum damage analysis to predict the initiation and ultimate stress for a [0/45/90/-45]ns, where n is the number of repeated section on one side of the mid-plane, laminated composite with straight vascular channels inserted along the mid-plane. A ply-level continuum damage model was used to predict the progression of damage within the unidirectional plies. Eight strain-controlled load paths were considered to generate the failure envelopes and predict knockdown factors useful for vascularized laminate design. [41] Straight and sinusoidal vascular channels within an orthogonally woven 3D textile have been studied using an interface-enriched generalized finite element method (IGFEM), which led to design maps for the required flow rate needed to maintain a certain maximum temperature within the composite. [42] [26] However, effective thermal properties were obtained using a highly idealized model for a 3D textile and the sinusoidal channel path does not follow the tow paths, making manufacturing such composites very difficult.

Aside from these numerical studies of actively cooled microvascular composites, some useful experimental studies have been published. An AFRL report showed that vascular channels could be embedded within a fiber/matrix composite via tube extraction, high temperature wax, soluble fiber, fiber extraction, or embedded tubes (creating lined channels). [43] Eckel et. al. conducted thermal experiments of stainless steel tubes and unlined vascular channels in carbon fiber composite laminate. Mode I mechanical test showed that the channels had little effect on the mechanical performance. It also showed very little difference between using lined and unlined channels within the composite, but this may be due to the relatively low thermal conductivity of the composite compared to channel lining considered. [44] Saeed et. al. demonstrated effective manufacturing processes for woven composites with vascular channels between layers using polytetrafluoroethylene wires that are placed in where the channels will be located and removed after curing. The work is very promising for the manufacturing of more complex vascular composites. [25] Kousourakis et. al. measured the effect of straight channels in laminated composites running along the longitudinal and transverse direction of the load, showing that transverse channels resulted in a more significant reduction in mechanical properties. A simple analytical model was proposed that matched the experimental data well for small channel diameters. [45] Norris et. al. conducted a similar study but focused on the effect of the embedded channels on impact damage, showing that the fabrication method used and orientation of channels significantly changed the morphology of the impact damage. Williams et. al. designed a prototype structure that provides active cooling via a circulatory system embedded into the face sheet supporting subsystems that produce heat. The active cooling path is controlled by a thermal valve, which allows cooling to occur when the temperature of the material reaches a designed temperature. [46]

Coppola et. al. experimentally studied the effect of vascular channels on the progression of damage of orthogonally woven 3D textiles with vascular channels under in-plane mechanical loads. Both straight and undulating channel designs were considered in the experimental studies, and acoustic emission and optical microscopy were used to detect and quantify the evolution of damage. It was observed that the strain at which acoustic emissions began, , which was very close to the elastic limit of strain, did not correlate to the ultimate strength of the composite, . The vascular specimens showed a noticeably lower compared to control specimens with no vascular channels, while was only lower for the undulating channel design. The authors concluded that there are poorly understood mechanisms that lead to the reduction in strength for the textile with an undulating channel design. This highlights the need for high-fidelity micromechanical damage models of these composites to provide insight into the effect of microvascular channels. Optical microscopy did show that the dominant damage evolving before final failure was transverse cracking, and that the undulating channel design resulted in significantly more cracks forming before final failure. However, the results showed that the channels had little effect on the overall mechanical properties, but this may be because the channel volume fraction was only 1.8% for the composite studied. [47] More recently, Coppola et. al. experimentally tested the ability of actively cooled polymer matrix composites (PMC) to retain mechanical performance under sustained thermomechanical loading. Two laminates composed of large sacrificial fibers and unidirectional plies were tested under a combined compression mechanical load and heat flux load applied to one side of the laminate. The channel volume fractions in the specimens were 1.5% for one layup and 3% for the second layup. Significant time to failure improvement was shown for the actively cooled PMCs. However, the failure modes of laminate were also significantly changed when the vascular channels were introduced. This highlights the need to account for the presence of microvascular channels in failure predictions, since they can fundamentally change the way a composite will fail. [48]

The literature available on the topic of microvascular composites has quickly grown within the last decade. Though the effect of microvascular channels in laminated composites and 3D textiles have been studied using numerical models that consider homogenized tow/ply material and small RVEs, no model has been developed capable of accurately predicting damage events under combined thermomechanical loads. Further, no model has considered the significance of defects or local fiber interaction with the channels. The models for vascularized 3D woven composites focusing on predicting damage initiation and growth are highly idealized or lack the detail necessary to accurately predict the initiation of damage in critical areas. A high-fidelity multiscale, progressive damage model of vascularized composites can provide the necessary insight to understand the effect of the channels on the mechanical performance and damage modes.

# Research Issues

Multiscale optimization of multifunctional materials that considers the impact of functional constituents on the progression of damage across scales offers the potential to accelerate the design and insertion of new material technologies. However, there are some significant challenges anticipated in the proposed work for the areas of multiscale methods, damage modelling, and visualization.

Within a multiscale analysis, determining when and where to increase the fidelity or detail of a region of the model is very important. Where a hierarchical model is used and before damage occurs at the lower scale, an RVE under periodic boundary conditions will provide the information needed for the next scale (equivalent to asymptotic homogenization), since the RVE is still linearly elastic. Once damage or yielding occurs, either a reduced order model or a semi-concurrent model, where the strain information is passed to the RVE to calculate the stress information, can be used to predict the behavior of the material past the elastic limit. At some point, damage will begin to accumulate at the smaller scale that is of a length comparable to the next larger scale considered. For example, microcracks at the fiber/matrix scale coalescence and eventually form a crack that should be accounted for discretely at the mesoscale. If the critical regions are known a priori, then the critical regions can be modelled at the microscale via a concurrent model within the mesoscale analysis. However, if the critical regions are not known a priori, then there will need to be a transition to a concurrent model. The criteria for this transition can be based on posteriori error estimates or based on something simple like the tangent stiffness, since the tangent stiffness approaches zero as the RVE approaches strain localization. Both of these types of criteria will be evaluated for this work. The problem of transitioning from a nonlinear state in the hierarchical model to an equivalent state in a concurrent model is the more difficult topic. The underlying issue is that an RVE or a reduced order model obtained form an RVE analysis is being used to model the material behavior for the hierarchical model, and the concurrent model requires the geometry to be generated and meshed for the domain of the larger scale that requires the increased fidelity. Mapping a damaged state from the RVE or reduced order model to the concurrent model requires full knowledge of the loading history to keep the error minimal. Some approximations can be made, such as assuming the created concurrent model is completely decoupled from the rest of the model and load it proportionally until it reaches the current state. This would introduce error, but it is more manageable than storing the full loading history for every element. Another possibility is to use a homogenized damage parameter in the hierarchical model to approximate a realistic damage state for the concurrent model in a mean-field sense. Strategies based on approximations will be evaluated to determine a method for transitioning between hierarchical and concurrent models with acceptable error, complexity, and computational cost. It should be noted that if the fine scales were modelled everywhere the RVE first reached the elastic limit, then the computational cost would be prohibitive.

Since damage localization at the microscale may not lead to component failure, damage models will be needed to predict the progression of damage. At the microscale, both yielding and the formation of discrete cracks are important to model. A plasticity model will be used to model the yielding in the epoxy resin, while a cohesive zone law will govern the opening of discrete cracks. In previous works, I used cohesive elements inserted between every continuum element in a refined 2D fiber/matrix mesh, but some mesh dependence was observed and many elements never opened up during the analysis. Currently, AFEM seems to offer a more suited method for modelling the initiation and growth of discontinuities within the matrix. With this method, cohesive elements will be inserted within an element once a critical stress state is reached. This should allow the extension to 3D progressive damage, rather than the anticipated significant mesh dependence of placing cohesive elements along continuum elements in a 3D mesh. However, cohesive elements will always be placed along critical interfaces, such as fiber/matrix or tow/resin, to model delamination. Many open fundamental questions remain in predicting microscale damage in fiber/matrix composites, such as can a microscale model predict useful fracture properties for the next scale and what is the effect of microstructure on the energy dissipation mechanisms for the various modes of failure. Much of this research will aim to provide insight to some of the open fundamental questions.

Finally, visualization of the very large datasets that will result from these analyses will require some new developments. Massively parallel visualization software packages have been seen significant development over the past few decades, such as ParaView and VisIt. However, finite element frameworks have typically not leveraged the emerging parallel visualization concepts. Consequently, a new method for storing the data and algorithms to combine large multiscale datasets will be required to visualize multiscale finite element results including information from all of the scales within the same visualization. This will be important for exploring and visualizing large multiscale analyses involving many scales. It is anticipated that a ParaView plugin will need to be developed to visualize these results.

Other challenges are anticipated as the research develops, but these three areas of the multiscale finite element method, progressive damage models, and visualization will be the key areas of new contributions.

# Research Plan

There many components to the multiscale damage model proposed for this work. A short summary of the anticipated methods, models, and software is provided in Table 1. Finally, a tentative timeline is given for the topics to be studied in this work along with the tasks involved in Table 2.

Table 1. A summary of tasks needed for the proposed work

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| --- | --- | --- |
| # | Task | Description |
| 1 | Implement AFEM in an in-house finite element code | AFEM will be used to describe discontinuities introduced by damage and is easier to implement within a standard FEA software compared to XFEM. |
| 2 | Use a cohesive zone formulation to govern opening of discontinuities within AFEM | A bilinear, mixed mode cohesive formulation has already been implemented and tested, but it will need to be implemented within the AFEM framework. |
| 3 | Implement a plasticity model | The plasticity model proposed by Ref. [49] will be used to capture the yielding that can occur within the epoxy matrix. The performance of a plasticity-cohesive zone model will be compared to the model proposed in Ref. [49], which combined the plasticity model with a continuum damage model and compared the predictions with experimental results. |
| 4 | Couple fine and coarse scale models via concurrent modelling using a multiscale projection method | There are numerous options on how to carry information from the finer model to coarser model. Some researchers use the finer model to create basis functions for the elements on the coarser grid, and the basis functions are found iteratively. Another option is to replace the domain of the coarse grid with a fine grid and couple the two problems along the coarse-fine boundary. This work will use the latter technique with a multiscale projection method developed by Loehnert and Belytschko for upscaling the fine scale solution to the coarser scale. [50] |
| 5 | Extend existing tools and integrate TexGen into the analysis framework to allow automatic generation of microscale and mesoscale geometry | To generate the geometry at the microscale and mesoscale, existing tools will be integrated into the computational framework. For the generation of fiber/matrix geometries and RVEs, a tool originally developed by Ross McLendon will be extended. For the generation of 2D and 3D textile composite geometries, TexGen will be directly integrated into the framework via the C++ API provided with the tool, though it is expected that some extension of their software may be needed to include microvascular channels. |
| 6 | Integrate an existing mesher for creating meshes at each scale based on the generated geometry | The problem of meshing complex geometries is an extremely challenging problem, and this work will use existing tools to automatically mesh the microscale and mesoscale geometries. For the microscale, a triangle based meshing library is currently being used to create random 2D fiber/matrix meshes. For 3D microscale meshes, a different meshing tool will be required. TexGen provides an ability to create meshes of textiles automatically with tetrahedral elements. There are other general meshing tools available commercially. Tools like MeshSim and HyperMesh will be considered for this work. Hexahedra elements is preferred over tetrahedral elements due to better combination of efficiency and accuracy. If AFEM or XFEM are implemented within the framework, then the elements do not necessarily need to conform to material boundaries, which makes meshing less challenging but creates other concerns regarding accuracy. |
| 7 | Extend existing HPC FEA framework to include damage modelling and coupling across scales | The computational cost of the proposed problem will far exceed resources available on a high-end workstation, with tens of millions of elements anticipated to be needed for a multiscale analysis of the proposed problem. To overcome this challenge, high-performance computing will be required that leverages massively parallel computational architectures with intelligent load balancing. The in-house standard FEA framework developed over several decades has recently been extended to handle distributed meshes has been shown to scale well up to 10 million degrees of freedom. The framework has not been tested for larger problems, but it is expected to scale well for the sizes of problems considered in this dissertation. The massively parallel FEA framework will need to be extended to include damage modelling and coupling across scales. There is an existing open source multiscale coupling framework available, PEXIS, which interfaces with Abaqus and LAMMPS. Some concerns exist regarding the numerical efficiency of this framework, but the in-house massively parallel FEA tool used in this work may be directly integrated into PEXIS to allow multiscale coupling with other tools. |
| 8 | Extend an existing ParaView reader to dynamically combine multiscale data | The analysis at each scale will generate very large datasets that can be visualized individually. However, to visualize the effect of the microscale phenomena on the larger scales, the data from each scale need to be combined into one visualization. ParaView offers the ability to visualize large distributed datasets using high-performance computing systems and the ability to write custom readers and plugins. A ParaView reader has been developed to visualize distributed FEA data, but it will need to be extended to incorporate the data from multiple scales within the same visualization. |

Table 2. Anticipated time required for each topic and publications

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| --- | --- | --- |
| Topic and Anticipated Publications | Tasks Involved | Estimated Time Required |
| **Develop a mesh-independent damage fiber/matrix model using AFEM, a cohesive zone model, and a plasticity model**  *Publications: “The prediction of progressive damage in fiber/matrix composites under complex loads” and “The effect of microvascular channels on the progression of damage in laminated composites”* | 1, 2, 3, 5, 6 | 8 months |
| **Extend the damage model to massively parallel FEA framework**  *Publications: “A distributed high-performance finite element framework for the prediction of damage in advanced composites”* | 7, 8 | 6 months |
| **Develop multiscale FEA model to consider the fiber/matrix and textile scale via a concurrent model for 3D textile composites**  *Publications: “A high-fidelity progressive damage model for 3D textiles with microvascular channels”* | 4, 5, 7 | 6 months |

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