

Defects Assessment of Composite Laminates from Scanning to Modeling

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Abstract: Defects induced in the fabrication and application of composite laminates have substantial influence on the performance of composite structures. The effects of these undesired defects on the static and fatigue mechanical behavior are very important in the reliability and sustainability assessment. An integrative approach is developed to evaluate the major defects including voids and ply waviness from Computed Tomography (CT) scanning to multiscale modeling. Based on the CT scan results, voids and ply waviness can be captured quantitatively. These defects can be analyzed by using the represented volume element (RVE) model and statistical model in micro scale and their effects on the material properties (stiffness, strength and fracture toughness) are included into the macroscale model using a possibilistic uncertainty model. Ply waviness information can be extracted by an image processing method and it will be described explicitly in the finite element model with curved ply interfaces. Cohesive elements can be selectively inserted into the critical interfaces based on the stress analysis using an automatic mesh generation method. The effects of voids and ply waviness on the volume fraction of the composite laminates are also considered by using the rule of mixtures. The integrative approach is validated using the test data of an L-shape beam under four-point bending.

Keywords: Composites, Damage, Delamination, Failure, Multiscale, Curved Beam, Computed Tomography Scanning, Defects, Void, Ply Waviness

1. Introduction

Defects in composite laminates can be induced in the fabrication and application process, which reduce the reliability and sustainability of composite structures. The assessment of the effects of defects on the mechanical performance is very important in the application of composite materials. Recently, CT scanning was introduced to examine the defects of the composite laminates as a nondestructive inspection (NDI) method and its ability to quantitatively characterize the geometry of defects has been investigated (Schilling, 2005; Kastner, 2010; Amenadar, 2011; Nikishkov, 2013 and 2014).

Despite the difficulties in the image processing to extract the defects geometry, modeling the defects in the finite element model is also very challenging. Various forms of defects are randomly

distributed in the composite laminates and an advanced image processing technique is required to filter the noise and identify the defects. The defects derived from CT scanning could not be modeled directly due to the irregular geometry and large size range. Including each defect into the finite element mesh is not manageable because it could result in huge computational costs. The present characterization approach of defects is mainly based on a manually driven process and most of the analysis models are two-dimensional based on a cross-sectional view of a composite specimen with defects (Pansart, 2009; Lemanski, 2013; Cinar, 2015).

In this study, an integrative modeling framework from CT scanning to multiscale modeling is proposed. Defects including void and ply waviness extracted from CT scanning need to be processed and evaluated before the implementation into a finite element model. Implicit and explicit modeling approaches are developed for ply waviness modeling based on a mesh generation method and a multiscale model, respectively. Voids are integrated into the finite element model using a mapping approach and their effects on material properties are characterized using a microscale model. An extruding mesh generation method and a cohesive insertion method are also developed to assist the user in model generation. To demonstrate the solution process for the integrative modeling approach, a curved L-shape beam is modeled with its ideal and wavy plies configuration.

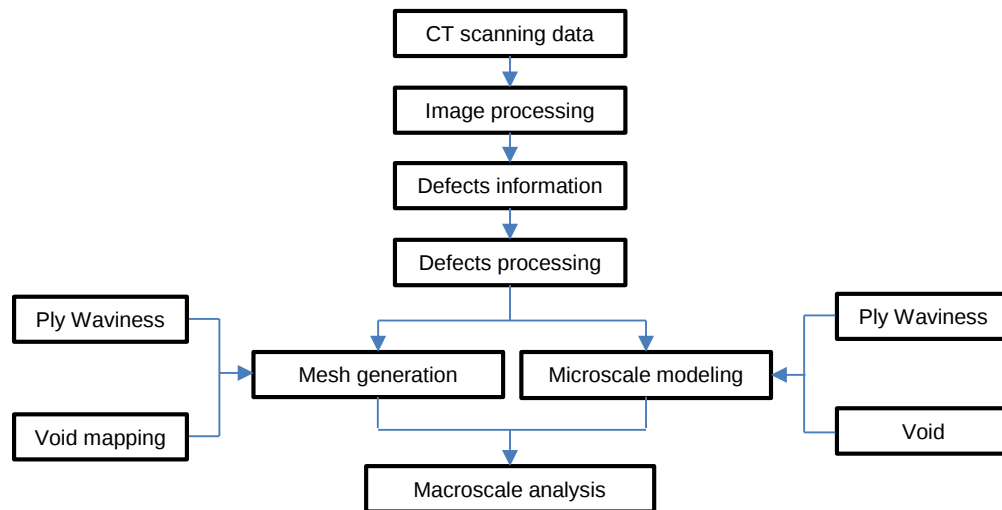


Figure 1. An integrative modeling framework from CT scanning to multiscale modeling.

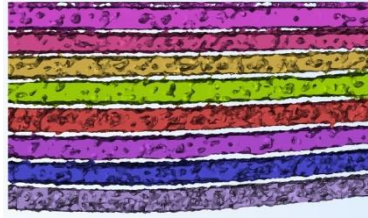
2. Modeling Framework

An integrative modeling framework is developed from CT scanning to multiscale modeling, as shown in Figure 1. Two major types of defects, void and ply waviness, are analyzed in the model. Through an image processing method, voids and ply interfaces in the composite laminates can be extracted. However, the raw information of voids and interfaces cannot be used directly due to the

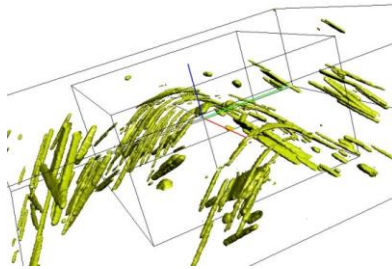
inevitable noise and numerous negligible defects. The defects need to be processed and evaluated before being implemented into the finite element model. Based on the experimental observation, it is not practical to model the void explicitly in macroscopic scale, which could result in an unreasonably large mesh. After the analysis of defects, a multiscale modeling approach is adopted to integrate the defects into the finite element model. The effects of defect on the mechanical behavior of composite laminates are studied by using a representative volume element (RVE) in microscopic scale. The material properties of an element with defects are degraded accordingly to represent the defect influence. A continuum damage mechanics (CDM) model is then employed to simulate the failure of the composite structure in macroscopic scale.

2.1 Defects Processing

An example image processing result with ply and void information is given in Figure 2. It can be seen from Figure 2a that the ply interfaces are very irregular, which is not applicable for finite element meshing. Surface smoothing is necessary to create a reasonable finite element mesh. Numerous voids can also be seen in Figure 2b and it is not practical to simulate each void regardless of its size. Under the constraint of the fiber and surface tension, most of the voids have a shape similar to a cylinder or ellipsoid. Based on an approximate approach, the voids can be characterized by its length and radius using a cylinder or ellipsoid. The void with negligible characteristic length can be excluded in the finite element model.



(a)



(b)

Figure 2. Ply and voids information extracted from CT scanning: (a) ply, (b) voids.

2.2 Defects Modeling

After defects processing, implicit and explicit approaches can be applied in the simulation of ply waviness and voids in composite laminates.

2.2.1 Ply Waviness

Two approaches are adopted to describe the ply waviness. The explicit approach is to build the finite element mesh directly following the extracted interface information from CT scanning. According to the nature of composite laminates, a mesh generation method is developed by extruding a two-dimensional mesh to a three-dimensional laminates structure, as shown in Figure 3. This mesh generation method can be applied to planar and curved composite laminates. Based on the ply waviness information, wavy plies can be generated by controlling the coordinates of the nodes at the ply interfaces. During the mesh generation process, local coordinates are calculated and assigned to each element and cohesive elements are inserted into the interfaces per user's request.

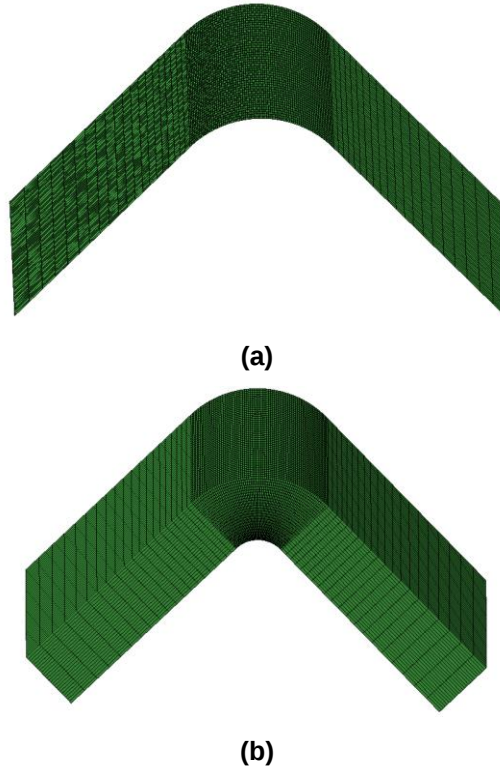


Figure 3. Three-dimensional mesh generation from a two-dimensional mesh by extrusion: (a) two-dimensional mesh and (b) Three-dimensional mesh.

Based on the microscale model, the ply waviness effect can be described using the degraded material properties. Therefore, it is not necessary to align the finite element mesh with the ply interface. This implicit method provides more freedom and hence reduces the complexity in the mesh generation. To further reduce the burden on the user during mesh generation, a general approach is developed for the cohesive element insertion in the ply interface for an existing mesh. The algorithm of the cohesive element insertion method is shown in Figure 4. This method doesn't have any requirements on the stacking direction of the mesh. To aid mesh generation, an Abaqus user subroutine, ORIENT, is also developed for the assignment of the local coordinates in an existing mesh.

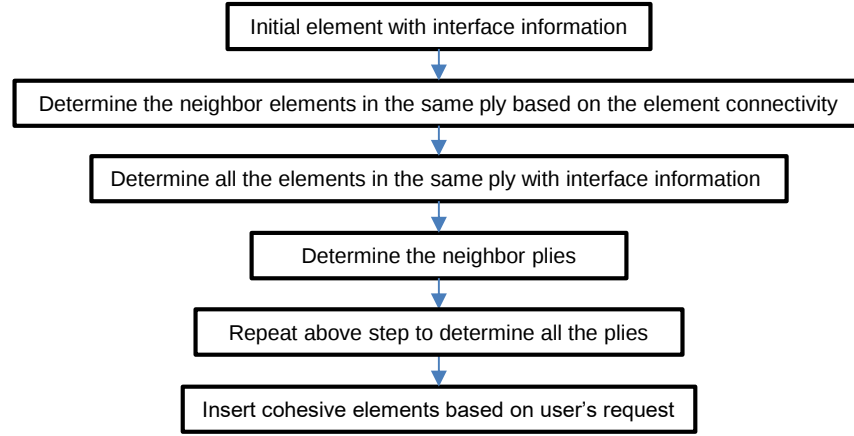


Figure 4. Cohesive element insertion method.

Nonuniform ply waviness can lead to nonuniform thickness in the plies, which indicates the volume fraction change of the matrix and fiber. The thickness change is mainly induced by the flow of matrix during the cure process and hence the volume change of the ply can be contributed to matrix. The influence of the volume change on the stiffness of ply level can be estimated using the rule of mixtures, given by

$$E_c = fE_f + (1 - f)E_m \quad (1)$$

where E_c is the elastic modulus in fiber direction; E_f and E_m are the elastic modulus of fiber and matrix, respectively; f is the volume fraction of fiber.

The volume fraction of fiber can be given by

$$f = f_o \frac{t_o}{t_i} \quad (2)$$

where f_o is the original volume fraction of fiber; t_o and t_i are the original and current ply thickness, respectively.

2.2.2 Voids

Due to the scattering in the distribution and shape of numerous voids, the computational cost is unmanageable to explicitly simulate each void in the finite element simulation. In the defects processing, unimportant voids are filtered out. For the remaining voids, a void mapping approach is developed to map the voids into the finite element mesh. The work flow for void mapping and subsequent multiscale modeling is shown in Figure 5. The void surfaces are described using triangular mesh after extraction and the voids intersection with finite elements can be calculated. To save the computational cost, a two-step intersection detection method is adopted. In the first step, the intersection is detected based on the center distance between the void and element. If the center distance is larger than the sum of the void and element characteristic length, the void and element could not intersect with each other. Otherwise, the computational geometry method for intersection detection between two polyhedrons can be adopted in the second step. Once the intersection is detected, the void volume fraction in the element can be calculated using the intersection calculation method between two polyhedrons.

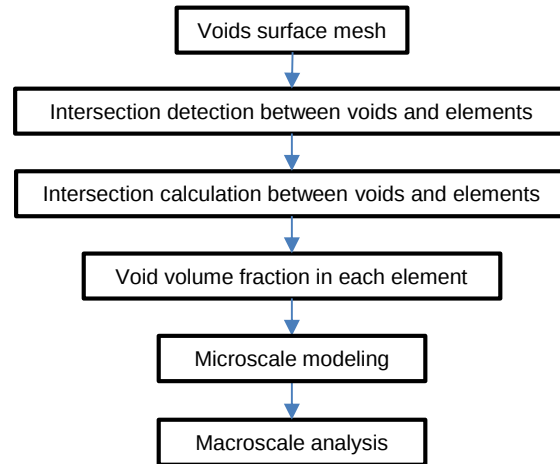


Figure 5. Void mapping and multiscale modeling.

With the derived void volume fraction, a microscale model can be applied to determine the effects of voids on the macroscale material properties of composite laminates according to the character of the void.

2.2.3 Microstructural Modeling

As an integral step of the entire framework, microstructural modeling explicitly models ply waviness and voids and quantify their influences on the pointwise effective properties of the composite laminates. The multiscale computation involves two length scales: (1) the macroscopic scale where effective properties of composite laminates are evaluated; and (2) the microscopic

scale where microstructural details including wavy fibers and voids are explicitly modelled within a representative volume element (RVE). The two scales are linked through an extended periodic homogenization approach, in which the microscopic analysis is based on a multibody modeling in the context of a cohesive zone fracture simulation. Figure 6a provides details of the workflow. Particular emphasis is placed on the periodicity of the microstructural model. As the homogenization theory requires materials with infinitely small microstructures, it is assumed that the displacement and stress fields are periodic across all boundaries of the RVE. To comply with these assumptions, all aspects of the model including the geometry and the mesh have to be periodic. We have developed preprocessing code to ensure that periodicity is enforced for the model with randomly generated fibers and voids. An example RVE can be found in Figure 6b. Figure 6c-d shows the fibers and voids, respectively. The periodicity is demonstrated in Figure 6e. It is readily seen that as a fiber or a void is cut by a boundary of the RVE, the part outside of the RVE is moved to the other side of the RVE as an internal part to achieve the periodicity. The periodic geometry is then meshed in a way such that two opposite faces have exactly the same surface mesh. Based on this mesh, cohesive elements are inserted between neighboring elements. Figure 6f demonstrates an example of the cohesive element insertion protocol, in which solid elements are in green and cohesive elements are in silver. Here, cohesive elements are given finite thicknesses for visual clarity. Zero thickness is used in production runs.

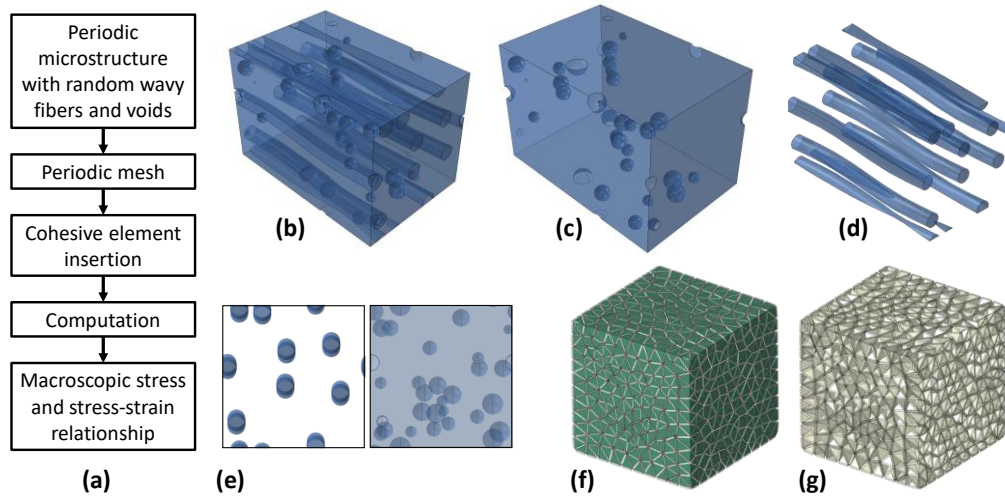


Figure 6. (a) Flow chart of microscale modeling; (b-d) an example of composites with random wavy fibers and voids; (e) periodicity of fibers and voids; (f-g) an example finite element model (green: solid elements; silver: cohesive elements).

Two examples of microstructural modeling are compared in Figure 7 to demonstrate the effect of fiber waviness on the tensile behavior of fiber reinforced composites. Figure 7a-c shows a RVE

model that has a straight fiber. The transverse plane has a size of a by a ($a = 50$), the length is $2.5a$, and the fiber has a radius $r = 0.25a$. Linear 8-node elements are used to model the matrix (Figure 7a) and the fiber (top of Figure 7b), respectively. Cohesive elements are generated within the fiber (bottom of Figure 7b), within the matrix (Figure 7c) and at the fiber/matrix interface (middle of Figure 7b). As a macroscopic strain is applied to the RVE vertically, damage progression is observed by visualizing cohesive elements entering the softening regime (Figure 7d). Meanwhile, microcracks are generated as shown in Figure 7e. Mesh dependency is noted in the crack path results, which should be alleviated by using finer meshes. The stress-strain curve from this analysis is shown in Figure 7f, based on which both the elastic modulus and the ultimate tensile strength can be extracted. To reveal the waviness effect, another RVE with the same size but a wavy fiber is modelled as shown in Figure 7g. The waviness is modelled by a sine function with an amplitude of $0.6r$. The stress-strain curve along the loaded direction is plotted in Figure 7f. Fiber waviness shows negligible influence on the effective stiffness in this transverse direction. However, effective strength is significantly reduced by over 30%. Different from the previous case where the materials fail simultaneously along the fiber, the fiber waviness in this case makes damage progression significant along the fiber direction. As shown in Figure 7h, microcracks extend to points A and B first, and then propagate further leading to final failure of the RVE.

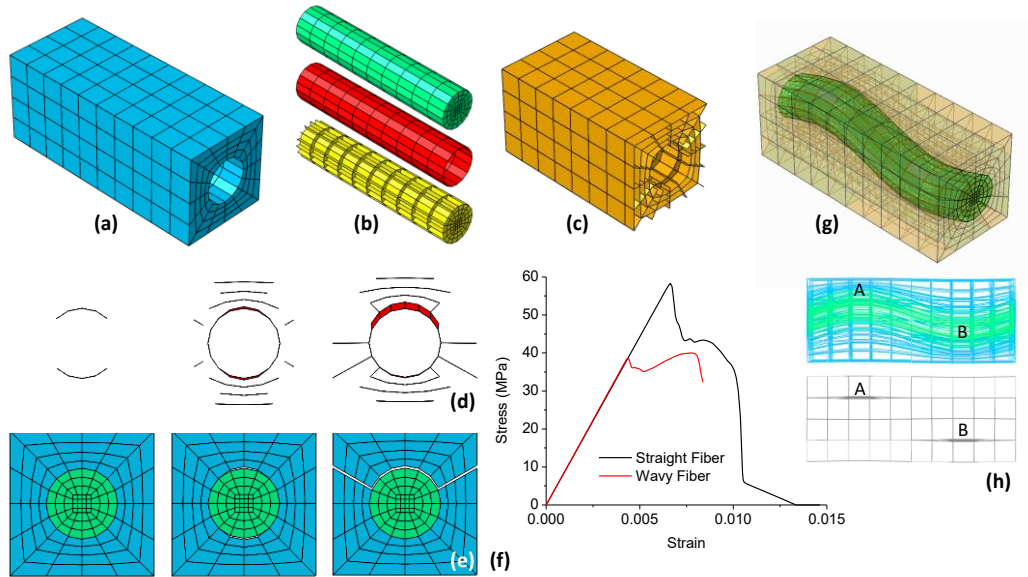


Figure 7. Effect of fiber waviness on the mechanical response of a unit cell model:
 (a) matrix; (b) fiber, and cohesive elements at the interface and in the fiber; (c) cohesive elements in the matrix; (d) damage evolution; (e) deformed microstructure; (f) stress-strain curves; (g) microstructure with a wavy fiber; and (h) side view of elements, and locations where crack are initiated.

Further development in microscale modeling will allow us to use experimentally characterized defect statistics to achieve statistically valid effective properties. Latin hypercube sampling and its generalization will be used for efficient sampling of microstructures. The method described above will be used for analyzing these microstructures. Surrogate models (e.g. Gaussian process) may be used for problems with high computational costs.

3. Demo example

To study the effects of defects on the mechanical response of composite laminates, an L-shape beam made of AS4/8552 prepreg under four-point-bending is modeled. The design of the L-shape beam specimen and testing fixture follows the ASTM standard (ASTM D6415), as shown in Figure 8. The thickness of the specimen is 0.162 in and the layup is $[45, 90, -45, 0, 0, -45, 90, 45]_3$.

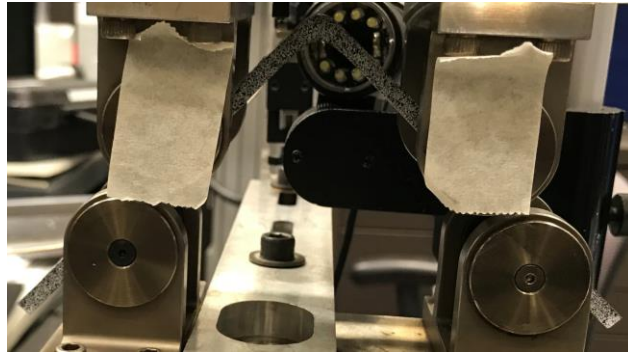


Figure 8. L-Beam testing setup (ASTM D6415).

CT scanning was performed before the test and one side view is given in Figure 9. Obvious ply waviness and voids can be observed in this region. The voids information was also extracted by image processing and the result is shown in Figure 2b.

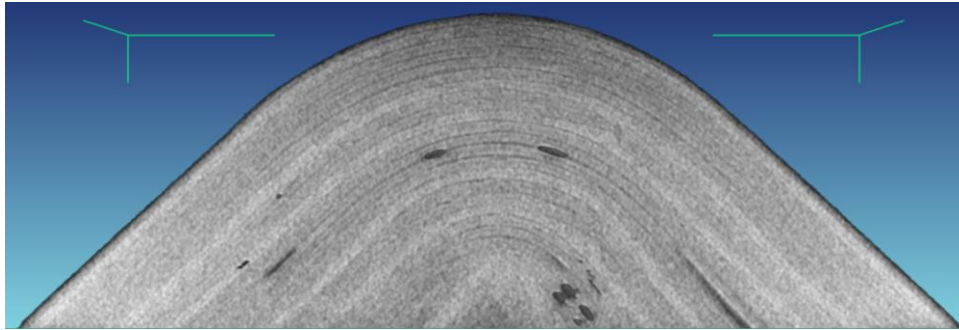


Figure 9. CT scanning side view of curved part of the L-Beam.

Based on the ply waviness and void information, a finite element model is built using the developed extruding method. Delamination is the dominated failure mode based on experimental observation and hence initial delamination is introduced in the model according to the void process result. The mesh of the finite element model is shown in Figure 10. Meanwhile, a finite element model without ply waviness is also built as a reference solution, as shown in Figure 11. There is a resin rich region in the inner corner formed during the fabrication. The interface delamination is modeled using Abaqus cohesive element.

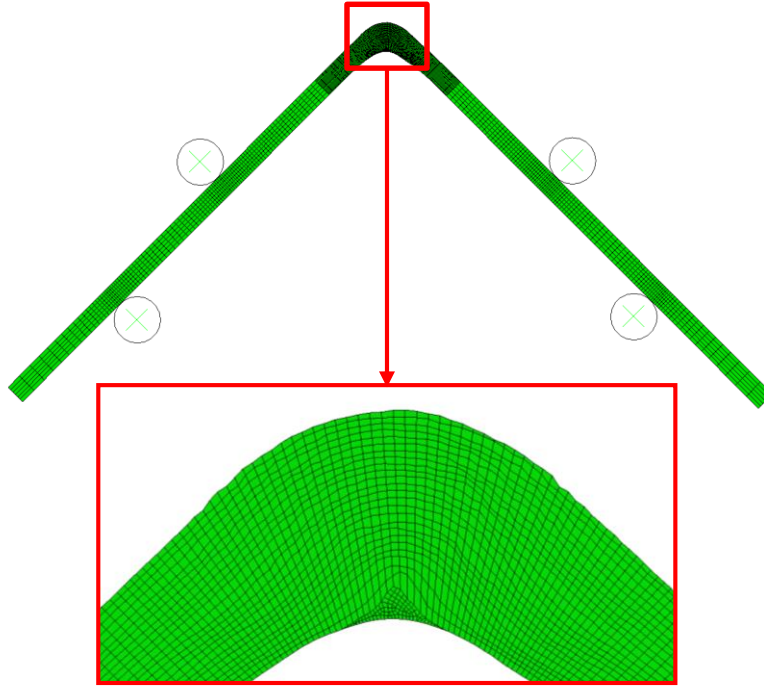


Figure 10. Finite element model of the L-Beam with ply waviness.

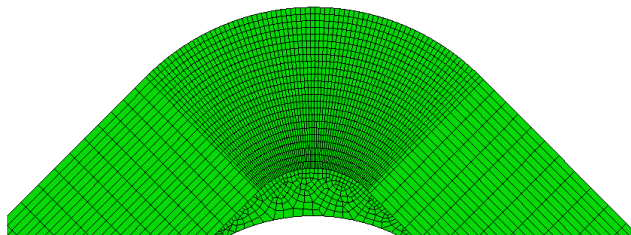


Figure 10. Finite element model of the L-Beam without ply waviness.

The material properties are collected from NIAR report (Marlett, 2011) and a reference book (Pavan, 2000), as listed in Table 1.

Table 1. Material properties of AS4/8552 Unidirectional Graphite/Epoxy Prepreg

Elastic Properties	E_{11} (Msi)	E_{22} (Msi)	ν_{12}	ν_{23}	G_{12} (Msi)
Nominal Value	19.09	1.34	0.3	0.42	0.7
Strength Properties	Y_t (ksi)	S_{12} (ksi)	G_{lc} (psi·in)	G_{llc} (psi·in)	
Nominal Value	9.27	13.28	0.94	4.71	

The predicted load displacement curves are compared with the test data, as shown in Figure 11. It can be seen that the peak load is over predicted using the model without defects while the predicted peak load using the model with defects is much closer to the testing measurement. The predicted failure patterns are also compared with the testing result, as shown in Figure 12. It can be seen that the predicted failure patterns using the model with defects agrees well with the testing result, while the predicted delamination location using the model without defects is in the interface closer to the bottom surface. Besides the central interface delamination, delaminations are also predicted in the interfaces near the resin rich region. Due to the interface in this region, it is very difficult to identify and ply waviness in the model may be overestimated. In general, the model with defects can capture the failure behavior and hence provides a more accurate failure strength prediction for the composite laminates.

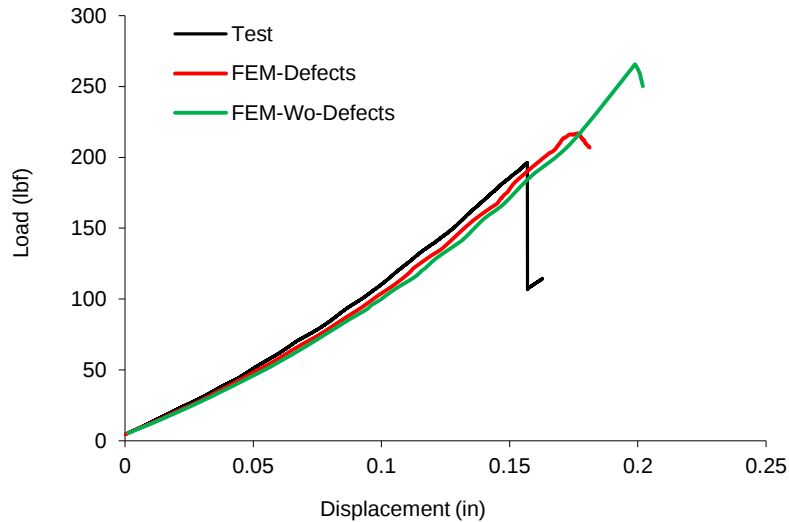
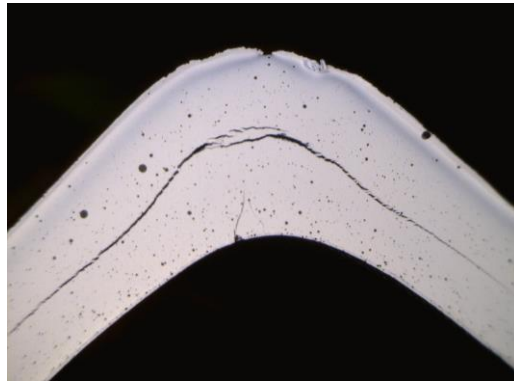
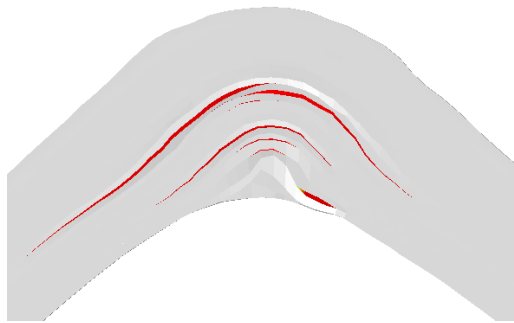


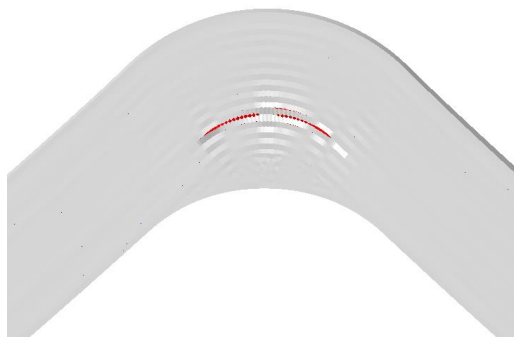
Figure 11. The comparison of load displacement curves.



(a)



(b)



(c)

Figure 12. The comparison of failure patterns: (a) test, (b) model with defects and (c) model without defects.

4. Conclusions

An integrative framework is proposed for finite element simulation from CT scanning to multiscale modeling. Under this framework, defects need to be analyzed based on their geometry characteristic before being integrated into finite element model. Two major types of defects are considered, including ply waviness and voids. Two approaches, an explicit and an implicit approach, are developed for ply waviness modeling. The explicit approach is realized by a mesh generation method based on the ply waviness interface geometry from image processing. The implicit approach is based on a microscale model, which doesn't require the alignment of the mesh to exact ply interface. The developed microscale model is also adopted to characterize the effects of voids on the material properties. Through a void mapping approach, voids are simulated in the finite element model without explicit representation of their geometry. A cohesive insertion method is also developed to assist users with model generation.

The developed modeling approach is applied in the simulation of an L-shaped curved beam under four-point bending. Ply waviness is explicitly modeled and void effects are considered by introducing initial delaminations. Good agreement is achieved between simulations and testing in terms of load displacement response and failure patterns. The peak load is over predicted using the finite element model without defects, which indicates the substantial impact of the defects on the mechanical response of composite laminates.

5. Acknowledgement

This work is funded by Naval Air Warfare Center, Aircraft Division under the Contract of N68335-17-F-0219 with Mr. Nam Phan as program monitor. The authors are grateful to Dr. Waruna Seneviratne and his team at National Institute for Aviation Research at Wichita State University for providing us defects characterization and static test data and Mr. Jason Sun and Dr. Jessica Zhang from HexSpline3D in construction of geometric information of defects in the testing article.

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