Using Abaqus to Model Delamination in Fiber-Reinforced Composite Materials

Dimitri Soteropoulos, Konstantine A. Fetfatsidis and James A. Sherwood

Department of Mechanical Engineering, University of Massachusetts at Lowell, One University Ave., Lowell, MA 01854, USA

Abstract: The strength of laminated fiber-reinforced composite materials depends on the combination of the orientations of the stacked plies with respect to the applied loads and the state of the bonding between adjacent plies. Prior work has focused on developing forming simulations using Abaqus to track fiber orientations as a stack of fabric plies conforms to the shape of a mold. Knowing the final fiber orientations, cured composite properties can be defined to model the behavior of a resin-infused solid structural composite part. In this paper, a failure criterion and damage properties are investigated to model delaminations in composite parts. Delaminations due to Mode I failure are studied by testing unidirectional coupon specimens. Different modeling techniques are explored to evaluate their ability to replicate experimental results. In particular, conventional and continuum shells are used in conjunction with surface-based cohesive behavior to qualitatively conclude the credibility of the models.

Keywords: Composites, Delamination, Fracture, Failure, Finite Element, Mode I.

1. Introduction

Failure of fiber-reinforced composite materials can be generally characterized into two main modes: fiber/matrix failure (i.e., cracking) and delamination. Current failure theories typically predict fiber/matrix failure based on the maximum stress or strain limits of the material. Several research efforts have focused on studying the validity of the various fiber/matrix failure theories in different applications (Puck *et al.*, 1998)(Christensen, 1997). The current research focuses on understanding and predicting delamination failure in composites using Abaqus to complement existing simulations that track the evolution of the orientation of continuous fibers during forming processes. These forming simulations are capable of predicting part quality as a result of the manufacturing process (Jauffres *et al.*, 2009). Recent work has focused on characterizing the laminated composite properties to capture the structural stiffness of a part. The addition of failure criteria to predict in-service performance will allow for a model that can relate the manufacturing process to the in-service structural performance with respect to stiffness, the state of stress and the mode of failure (Fetfatsidis *et al.*, 2012).

Standardized testing techniques exist for determining the interlaminar fracture properties of unidirectional fiber-reinforced polymer-matrix composites (ASTM D5528, ASTM D6671). Different test methods exist depending on the mode of failure that is of interest. Commercial finite element codes such as Abaqus are used to simulate the experimental techniques and to validate the models. Variables such as delamination crack length and bond state can be monitored and compared to experimental results.

Typically, structural models of composite parts are built with multiple zones of 3-D (three-dimensional) continuum elements. However, in the current work, composite fabrics are modeled using a hybrid mesh of 1-D (one-dimensional) beam and 2-D (two-dimensional) conventional shell elements as described in the Section 2. A cohesive surface approach is used to bond multiple layers of fabric together in the finite element model and to specify failure criteria for capturing delamination. The current work uses Abaqus/Standard to compare the cohesive surface approach through the use of conventional shells and continuum shells. This comparison will provide insight into the accuracy of failure prediction depending on element selection. Overall, the implementation of cohesive failure criteria will further develop the current model for structural analyses.

2. Model description

A discrete description of the fabric is built using a mesh of 1-D and 2-D elements (Figure 1), where a unit cell represents the yarn interval in the fabric (Jauffres *et al.*, 2009). After a series of mechanical tests, the appropriate properties of the composite fabric can be obtained and implemented into the hybrid model via a user-defined material subroutine to capture the mechanical behavior of the fabric.

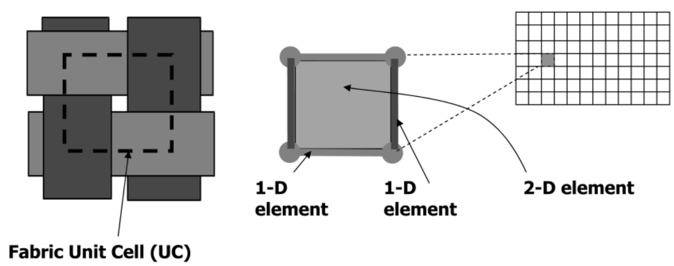

Figure 1. Principle of the discrete mesoscopic modeling using a combination of 1-D and 2-D elements.

The 2-D and 1-D elements in the fabric model are conventional shell (S4R) elements and (B31) beam elements, respectively. The level of refinement is based on the measured unit cell size. Abaqus/Explicit simulations of a punch-die setup are used to form the fabric stack into the shape of the die (Figure 2). The explicit formulation is used for these forming simulations due to the more robust contact algorithms relative to the implicit formulation.

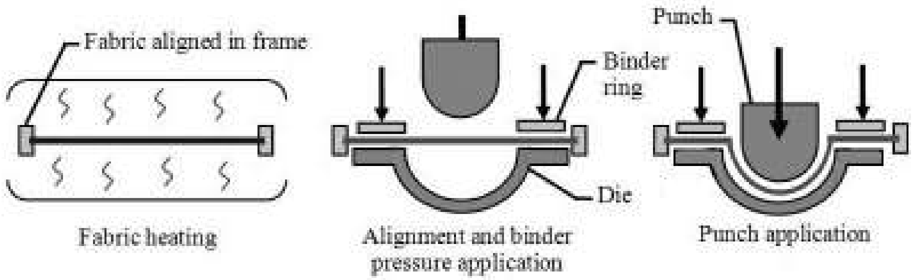

Figure 2. Punch-Die thermostamping schematic. (Fetfatsidis *et al.*, 2011)

The forming simulation captures the reorientation of the fabric yarns as they conform to the shape of the tool. Mechanical tests are performed on representative coupons to determine the structural properties that must be assigned to the shell and beam elements to capture the structural stiffness of the cured part (Fetfatsidis *et al.*, 2012). Multiple layers of fabric are bonded together using tie constraints between adjacent nodes and these tie constraints can significantly increase computation time. Furthermore, the tie constraints assume a perfect bond and without accurate failure criteria for the potential breaking of these bonds to account for delamination, the in-service performance and reliability of the part cannot be predicted.

Figures 3 and 4 show examples of composite structures that can be formed using stacks of woven and non-crimp fabrics, respectively. Figure 3 is a composite floor pan where woven fabrics have been formed to make the part a structural member for a lightweight car. The contours shown in the figure denote the degree of shearing in fabric as measured in degrees. Because the fabric yarns must shear to conform to the shape of the floor pan, the composite properties will vary throughout the structure. Figure 4 depicts a composite wind turbine blade. In both structures, material delamination is potential mode of failure that should be considered during field service.

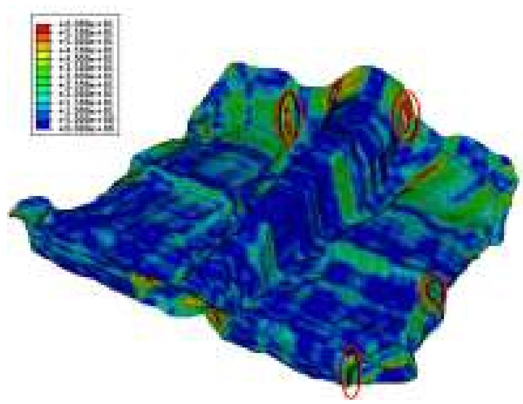

Fig. 3 Shear angle contour in degree for the 90/0 orientation.

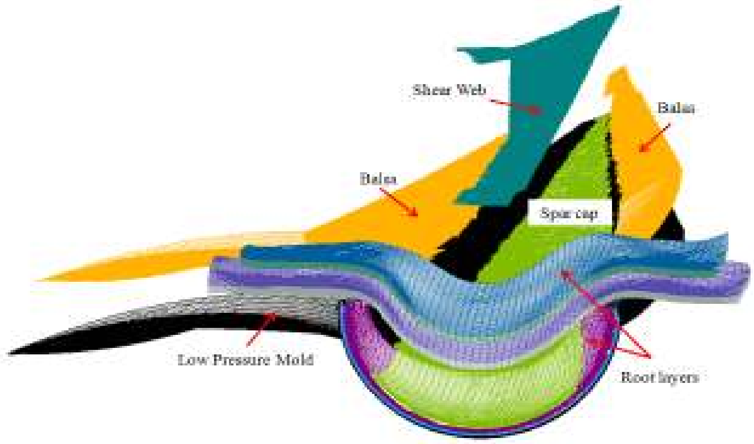

Figure 4. Exploded view of constituents of a 9-meter composite wind turbine blade.

The ability to predict delamination type failure in composite parts is a valuable tool in the design and optimization process. Modeling of this type of failure can be done through cohesive behavior. Defining cohesive behavior between contacting surface is a means to consider the initial bond strength between adjacent layers and to predict the possible failure of that bond due to various loading conditions. The importance of defining the bond strength is demonstrated in Figure 5 using a two-layer specimen that is loaded in compression (a). In a fist case (b) cohesion is not defined between the two layers and each layer acts independent of the other as the system is subjected to in-plane compression. In the second instance (c), cohesive properties are defined between the two layers and the coupon remains bonded and buckles out-of-plane due to the compressive load.

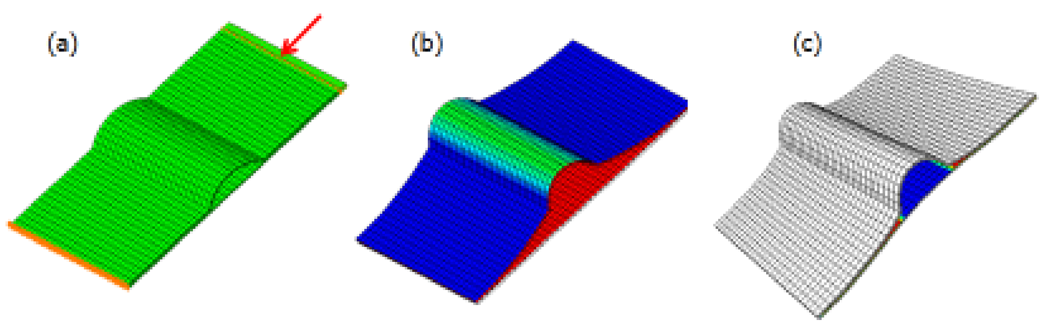

Figure 5. Two-layer coupon model showing (a) compressive loading/boundary conditions and the resulting bonding (b) without cohesive properties and (c) with cohesive surface properties.

The strength of the bond is a parameter which can be experimentally obtained. Standardized and non-standardized composite coupon tests can be conducted to determine the interlaminar fracture properties of composite laminates to simulate delamination failure. This research is a work in progress, so hypothetical bond strength is currently being used to demonstrate the potential value of the proposed methodology in capturing the delamination of a composite ply stack.

3. Material characterization

Brittle fracture in an isotropic material will occur in at least two stages: crack initiation and crack propagation (Boresi, A.P, 2003). Once crack initiation has occurred and a flaw has developed in the material, crack propagation can subsequently occur as a function of the loading conditions and the material properties. There are three pure modes of crack propagation in an isotropic material, as shown in Figure 6.

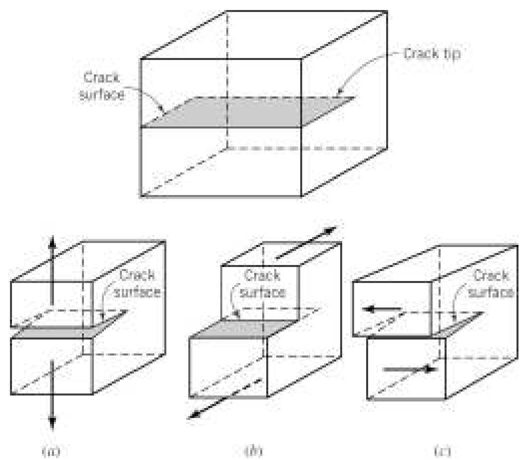

Figure 6. Three Pure Modes of Crack Propagation. (Boresi, A.P, 2003)

The fracture properties of composite materials are relatively complex due to their anisotropic behavior. While the three modes of failure (opening, in-plane shear and out of-plane shear) for a composite material are similar to the modes of failure for an isotropic material, the test methods used to characterize these failure modes are not the same. Mode I is typically referred to as the opening mode and an ASTM standard experimental test known as the double cantilever beam (DCB) (ASTM D5528) has been developed to address this mode. A schematic of a DCB test specimen is shown in Figure 7.

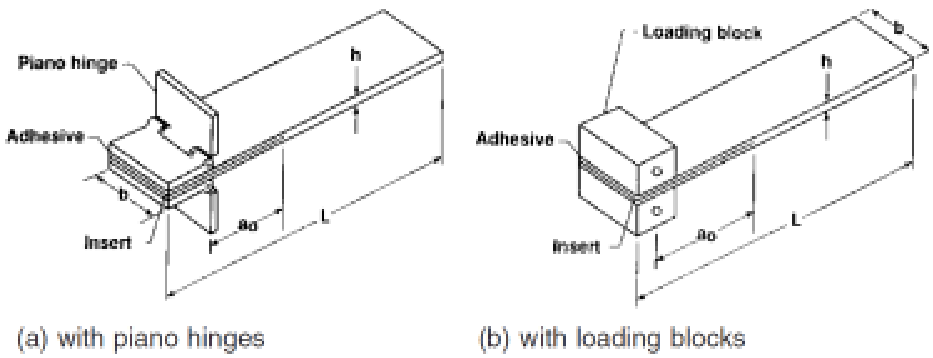

Figure 7. Double Cantilever Beam Specimen with (a) Piano Hinges or (b) Loading Blocks. (ASTM D5528)

The DCB setup shown in Figure 7 consists of a rectangular, uniform thickness, unidirectional composite specimen containing a nonadhesive insert on the midplane that serves as a delamination initiator (ASTM D5528). Specimens of dimensions shown in Table 1 are manufactured such that the variation in thickness for any specimen is less than 0.1mm. Since fracture testing of this sort depends on specimen and crack dimensions, the manufacturing tolerances are precise. An additional dimension that is not shown in the schematic of Figure 7 is the thickness of the nonadhesive insert. Standard calls for either a polymer or aluminum foil film to be used with a film thickness no greater than 13 μm.

Table 1. DCB Specimen Dimensions

Specimen Dimension	Value
L (Length)	125 mm (5.0 in)
b (Width)	20 to 25 mm (0.8 to 1.0 in)
a_o (Effective Insert Length)	50 mm (2.0 in)
h (Thickness)	3 to 5 mm (0.12 to 0.2 in)

Specimens are attached to the grips of a load sensing device such that slipping will not occur. A load is then applied with a crosshead displacement rate between 1 and 5 mm/min and load-displacement data are recorded. An optical microscope or other optical method may be used to record and measure the delamination length. If failure has occurred at the midplane of the plies and no slipping or debonding of the attachment methods is visible, then the sample should appear similar to Figure 8.

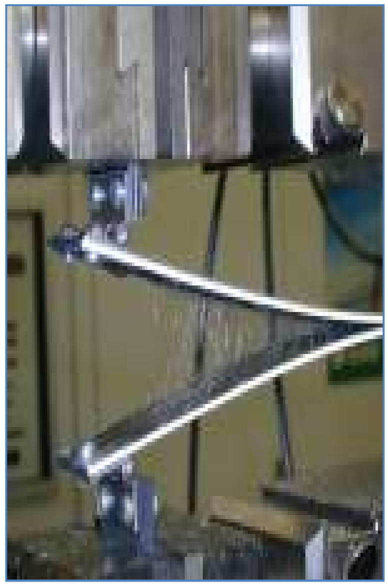

Figure 8. Example of Mode I Test. (Zwick, 2011)

The Modified Beam Theory, the Compliance Calibration, and the Modified Compliance Calibration are all methods used to calculate the interlaminar fracture toughness due to pure mode I failure. The beam theory used to calculate strain energy release rates, G_I, for this loading condition is given by:

$$G_I = \frac{3P\delta}{2ba} \qquad (1)$$

where:

P = load

δ = load point displacement

b = specimen width

a = delamination length

Equation 1 assumes a built-in condition where the double cantilever beam is clamped at the delamination front. Because the actual testing allows for rotation at this end of the beam, a modified version of the beam theory is used and the strain energy release rate is given by:

$$G_I = \frac{3P\delta}{2b(a+|\Delta|)} \qquad (2)$$

where Δ may be determined experimentally by generating a least squares plot of the cube root of compliance ($C^{1/3}$), as a function of delamination length (Figure 9)(ASTM D5528).

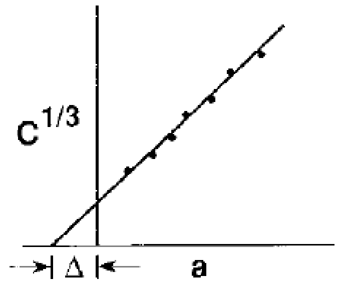

Figure 9. Modified beam theory. (ASTM D5528)

4. Finite element simulations

Now that the experimental methods for determining mode I fracture characteristics of fiber-reinforced polymer-matrix composites have been presented, simulations of fracture testing will be presented. Such simulations can be used to provide feedback to the design process by predicting crack initiation and propagation through composite structures upon loading. Bond strength properties between adjacent plies are defined using contact through cohesive surfaces. In lieu of mechanical test data in the current research, fracture properties from (Simulia, 2010) are used to demonstrate the proposed methodology.

4.1 Material Orientations

As stated previously, the forming simulations use a hybrid mesh of 2-D conventional S4R shell elements and 1-D B31 beam elements to model continuous fiber-reinforced polymer-matrix composite fabrics. Cohesive behavior can be defined between adjacent shell surfaces to account for the interlaminar bonding. Parametric studies can be performed to explore the credibility of the proposed methodology and if the results are element-type dependent. This paper compares finite element models with cohesive surface definitions for a conventional shell mesh and a continuum shell mesh. Future work will implement experimental data to validate the model results.

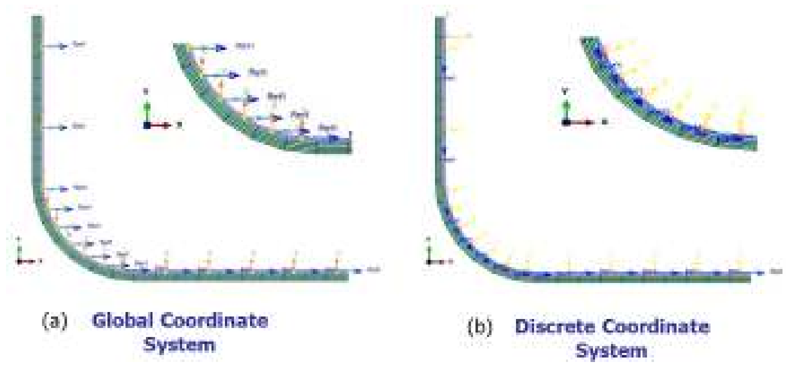

Figure 10. Curved plate material orientation with (a) global coordinate system and (b) discrete coordinate system.

Due to the orthotropic or transversely isotropic nature of composites, the material properties are commonly different in the three principal directions. The reinforcement of a composite is typically assigned the 1-direction, whereas the 2 and 3-directions are known as the transverse directions. Unlike 2-D conventional shell elements, the orientation of material properties must be explicitly assigned when using 3-D continuum elements.

Figure 10 shows a curved composite plate that has been built with continuum shell elements. In Figure 10a, the global coordinate system is used to define the material orientation. The global system does not rotate with the curvature of the model, thus incorrectly defining material properties for any portion of this curved plate not lying in the y-z plane. A discrete or local coordinate system, as is shown in Fig. 10b, can be used for which a normal and reference direction can be assigned depending on the reinforcement and transverse directions of the material. The importance of material orientation is demonstrated by the curved plate example shown in Figure 11. The U1 deflection for the model using the global coordinate system is 2.4 times that of the discrete coordinate system model.

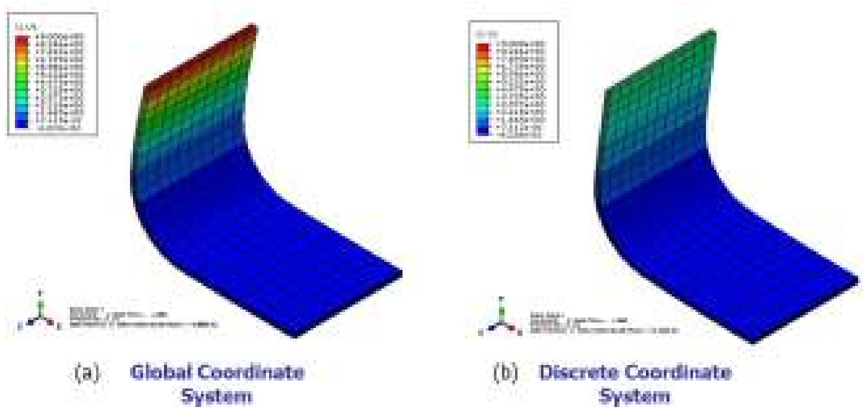

Figure 11. Curved plate U1 deflection using (a) global coordinate system and (b) discrete coordinate system.

4.2 DCB Simulations

Finite element models can be used to simulate the DCB experiment. Abaqus/CAE is used to create the geometry and prescribe boundary/loading conditions in the model. While the Maximum Stress and Tsai-Wu failure criteria are available in Abaqus, they do not model material degradation and are primarily used to compute damage initiation in a composite laminate due to the given stress/strain limits (Figure 12). There is no degradation in the material properties as a function of the magnitude of the effective stress or the Tsai-Wu parameter. Thus, these criteria are only useful for indicating whether or not a structure is damaged and the potential extent of the damage throughout the part.

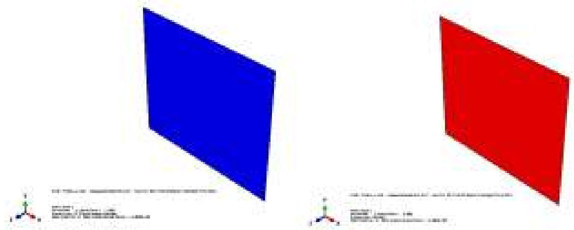

Figure 12. Tsai-Wu failure criterion.

Delamination can be modeled in any one of three ways in Abaqus, i.e. cohesive elements, VCCT (Virtual Crack Closure Technique), and cohesive surfaces. These methods take into account the transverse shear stresses which are of importance when considering delamination failure. Cohesive surfaces have been chosen for this research because of the ease of implementation into the current forming simulation models. Cohesive elements would require layers of elements to be generated in between plies of a laminate, which would be impractical for this research. Both damage initiation and propagation are parameters of interest with respect to modeling fracture, however through the use of VCCT only crack propagation can be modeled. To use a cohesive based model, the strain energy release rates must be determined experimentally using the testing methods discussed in Section 3. An example of a double cantilever beam specimen using continuum elements is shown in Figure 13.

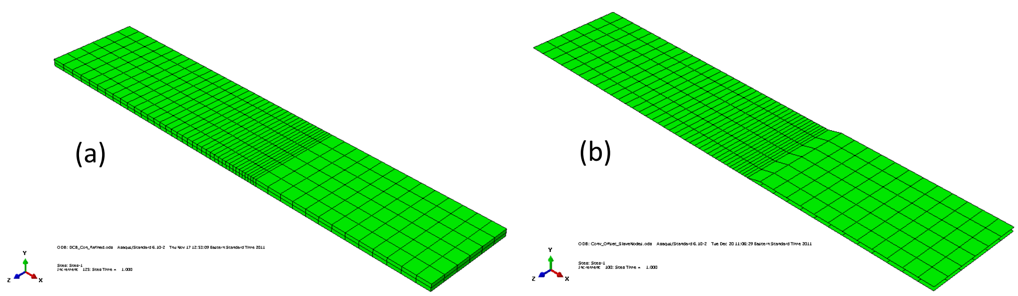

Figure 13. Double cantilever beam model using (a) continuum shells and (b) conventional shells.

For this paper, one of the fabrics used in the wind turbine blade was chosen for demonstrating the modeling approach, i.e. the biaxial ELT-5500 Vectorply non-crimp fabric (NCF) with material properties as listed in Table 2. Contact is defined at the bond interface using cohesive surfaces. Boundary conditions and loading are defined to replicate a pure Mode I fracture specimen. Load displacement curves result in a trend where there is a stiffness degradation of the sample after a linearly increasing slope of load as a function of displacement. The point along the curve where the data become nonlinear is the initiation of the crack in the sample (Figure 14).

Table 2. Vectorply ELT5500 Material Properties

Material Property	Value
E1	50000 N/mm^2
E2	15200 N/mm^2
Nu12	0.254
G12	4700 N/mm^2
G13	4700 N/mm^2
G23	3380 N/mm^2

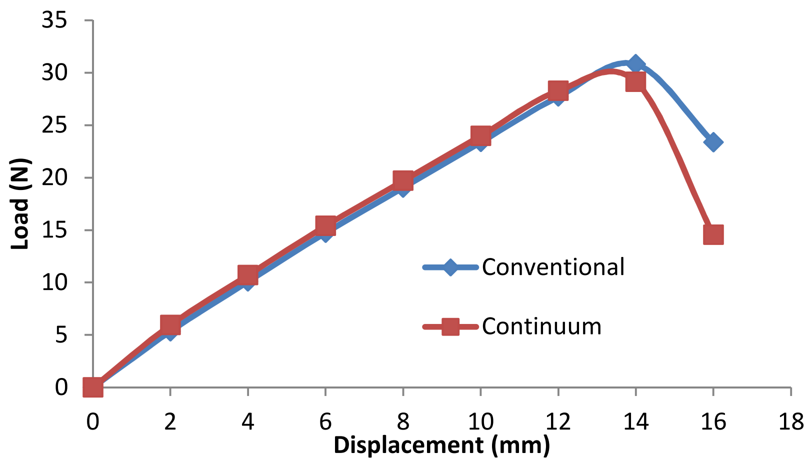

Figure 14. Load-displacement DCB data comparing conventional and continuum shell elements.

As shown in Figure 14, both element types exhibit essentially the same load-displacement response for the DCB test up to failure. However, after the delamination has initiated in the sample, the stiffness of the laminate decreases slightly faster for the continuum elements than for the conventional shells. This difference may be attributed to element type because the only difference between the models at this time is element type. Future work will explore the importance of mesh density. The red areas in the contour plots given in Figure 15, denote the damaged cohesive.

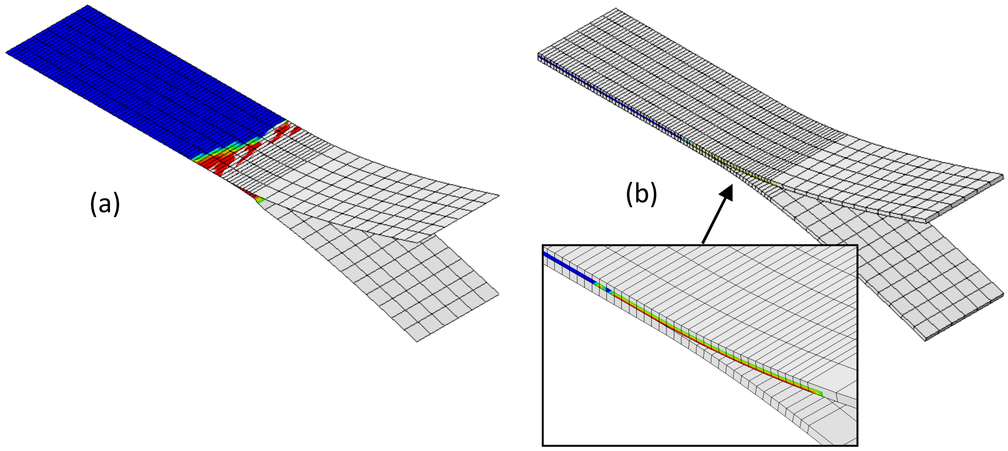

Figure 15. Double cantilever beam contours using (a) conventional shells and (b) continuum shells.

Further research is planned to be conducted to replicate composite fracture tests for other modes of failure. Correlation between conventional and continuum shell elements in these simulations will also be explored.

5. Conclusions

Failure criteria and damage properties were investigated to model delaminations in composite parts. Delaminations due to Mode I failure were modeled using Abaqus/Standard and show promise as a method for capturing the delamination phenomenon of laminated composites. using both conventional and continuum shell elements.

6. References

1. Puck, A., Schurmann, H.: Failure Analysis of FRP Laminates by means of Physically Based Phenomenological Models. Composites Science and Technology 58, 1045-1067, 1998.

2. Christensen, R.M.: Stress Based Yield/Failure Criteria for Fiber Composites. Int. J. Solids Structures Vol. 34, 529-543, 1997.

3. Jauffres, D., Sherwood, J.A., Morris, C.D., and Chen, J.: "Discrete mesoscopic modeling for the simulation of woven-fabric reinforcement forming" *International Journal of Forming*, Volume 3, Supplement 2, p.1205-1216, 2009.

4. Fetfatsidis, K.A., Soteropoulos, D., Petrov, A., Mitchell, C.J., and Sherwood, J.A.: Using Abaqus/Explicit to Link the Manufacturing Process to the Final Part Quality for Continuous Fiber-Reinforced Composite Fabrics. Simulia Customer Conference, 2012.

5. Fetfatsidis, K.A., Gamache, L., Sherwood, J.A., Jauffrès, D., and Chen J.: Design of an apparatus for measuring tool/fabric and fabric/fabric friction of woven-fabric composites during the thermostamping process. International Journal of Material Forming, DOI 10.1007_s12289-011-1058-3, 2011.
6. Boresi, A.P., Schmidt, R.J. Advanced Mechanics of Materials –6th Edition. John Wiley & Sons, Inc., New Jersey. 545-549, 2003.
7. ASTM Standard D5528.:Standard Test Method for Mode I Interlaminar Fracture Toughness of Unidirectional Fiber-Reinforced Polymer Matrix Composites[1]. ASTM International, West Conshohocken, PA, DOI: 10.1520/D5528-01R07E03, 2007.
8. "Fracture Toughness" (2011). http://www.zwick.co.in. Date last checked 12-Jan-2012.
9. Dassault Systemes. "Analysis of Composite Materials with Abaqus". Course Notes Memo. 2010.