NESTED MICROMECHANICAL AND STRUCTURAL MODELS FOR THE ANALYSIS OF DISCONTINUOUS LONG-FIBER THERMOPLASTIC COMPOSITE MATERIALS AND STRUCTURES

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Abstract: *This study presents a three-dimensional (3D) micromechanics-based nonlinear framework for the analysis of discontinuous long-fiber (DLF) thermoplastic composite materials and structures. The proposed material modeling framework is a nested micromechanical approach that explicitly recognizes the composite system within the cross-section of a DLF composite member. The overall modeling approach is able to predict both the elastic and nonlinear response of the composite material based on the in-situ properties and response of the fiber and matrix constituents. Coupon tests are used to calibrate the in-situ linear and nonlinear properties of the fiber and matrix. The nonlinear calibration of the matrix is done by using the overall axial shear stress-strain response generated from V-notch shear tests. The multi-scale constitutive framework is used with Abaqus for the analysis of DLF composite structures. The material subroutine (UMAT) is used to implement the DLF nonlinear micromechanical model. A damage modeling approach is also integrated with the micromechanical model to form a framework for the progressive damage analysis of DLF composite structures. The new "element deletion control by state variables" functionality in Abaqus/Standard version 6.14 is also employed as another approach for the progressive damage analysis. Several examples are presented to demonstrate the predictive capabilities of the coupled multi-scale material and structural analysis approach. The overall structural modeling framework is numerically efficient and accurate when compared with experimental response of DLF structural components.*

Keywords: *Composites, Constitutive Model, Micromechanics, Experimental Verification, Progressive Damage, Thermoplastic, Failure, Discontinuous Long-fiber, Multi-scale*

1. Introduction

One of the challenges remaining for composites in commercial aerospace applications is the ability to produce highly-complex three-dimensional (3D) components with an acceptable value proposition versus metals. Discontinuous long-fiber (DLF) thermoplastic composites are therefore introduced to provide complex-shaped composite parts with both part count and weight reduction advantages over simple loaded metal parts. DLF composites also bridge the gap between complex machined metal components and cost-intensive continuous fiber composite lay-up technologies.

Most DLF thermoplastic products are produced by chopping carbon fiber reinforced prepreg unidirectional tape into "flakes" or "chips" with predefined dimensions. This process enables cost-effective complex-shape metal replacement parts as seen in Figure 1. High thermoplastic resin viscosity results in very uniform fiber/matrix distribution throughout the component, including complex part features. Molded-in inserts and "net molding" capabilities result in cost-effective manufacturing (reduced trimming or assembly labor content, reduced material waste).

Flexibility in DLF composite part design and manufacturing also allows consolidation of multiple individual components into a single net-molded component which results in cost and weight savings. Thermoplastic matrix polymers for DLF materials in Aerospace applications are typically PEEK or PEKK [1].

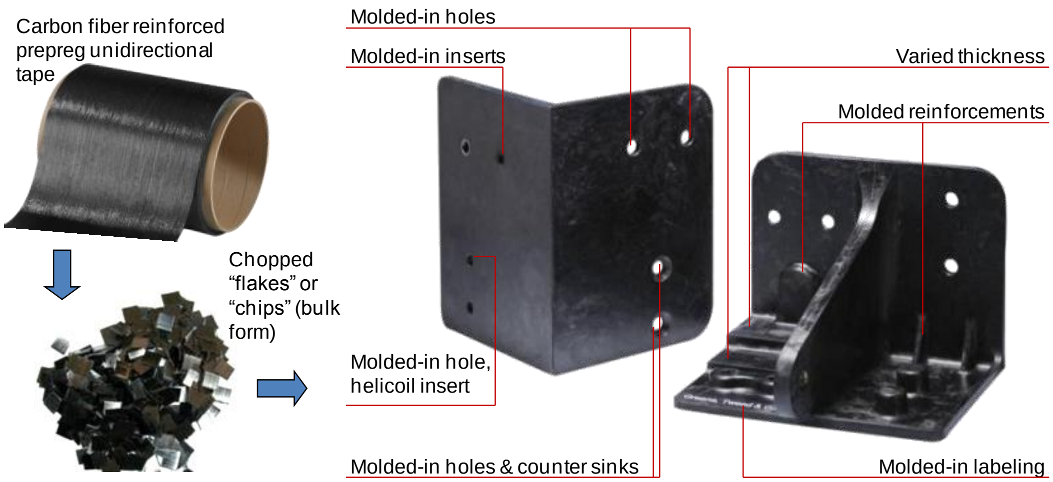

Figure 1. Greene Tweed's compression molded Xycomp® DLF parts

Certification of DLF parts currently is achieved by point design which requires testing large number of individual parts; hence, it is time consuming and expensive. As the use of compression molded DLF composites in the aircraft industry increases, there is a need to develop certification-by-analysis methods verified by limited experimental testing. However, there are currently no standard or established design and analysis methods for DLF composites due to the random fiber orientations, effects of material flow on fiber orientation, limited material test data, and nonlinearity in material behavior. Accurate modeling of DLF material behavior is therefore needed to establish proper stress analysis methodologies to predict DLF part performance.

To that end, this study introduces effective integration of 3D nonlinear micromechanical and structural models for the progressive damage and nonlinear analysis of DLF composite materials and structures. The DLF composite system is made of AS4/PEEK material. The proposed framework consists of linearized micromodel homogenization schemes and stress correction algorithms, which result in enhancing computational efficiency and accuracy. The effective material response is generated using a 3D micromechanical model consisting of a rectangular unit-cell with four fiber and matrix sub-cells. Approximate traction continuity and strain compatibility relations are expressed in terms of the average stresses and strains of the sub-cells. The fiber and matrix responses are explicitly recognized in this micromodel. The nonlinear elastic behavior is attributed to the matrix. The micromechanical modeling framework is integrated into a general 3D finite element (FE) code, Abaqus. The result is a new global-local nonlinear modeling approach for the analysis of DLF composite structures. A simple progressive damage approach is also utilized within the framework along with 3D Tsai-Wu failure criterion. The new “element deletion control by state variables” functionality in Abaqus/Standard version 6.14 is also employed as another approach for the progressive damage analysis. Compression molded DLF coupons and parts are tested and analyzed using the proposed multi-scale modeling framework. The framework shows very good predictive capabilities for the overall effective properties, nonlinear response, and ultimate load of DLF composites.

2. Nested micromechanical and structural framework for DLF composites

A combined micromechanical and structural framework is developed for the nonlinear and progressive damage analysis of DLF composites. A nonlinear 3D micromechanical model for the DLF medium is used to generate the effective in-plane and out-of-plane responses of the material. The proposed nested structural and material micromodeling approach is schematically illustrated in Figure 2. The upper level depicts an FE structural model using 3D continuum elements. At the lower level, a representative volume element (RVE) in the form of a unit-cell (UC) is used at each Gaussian material point in order to generate an effective homogenized nonlinear response for DLF medium.

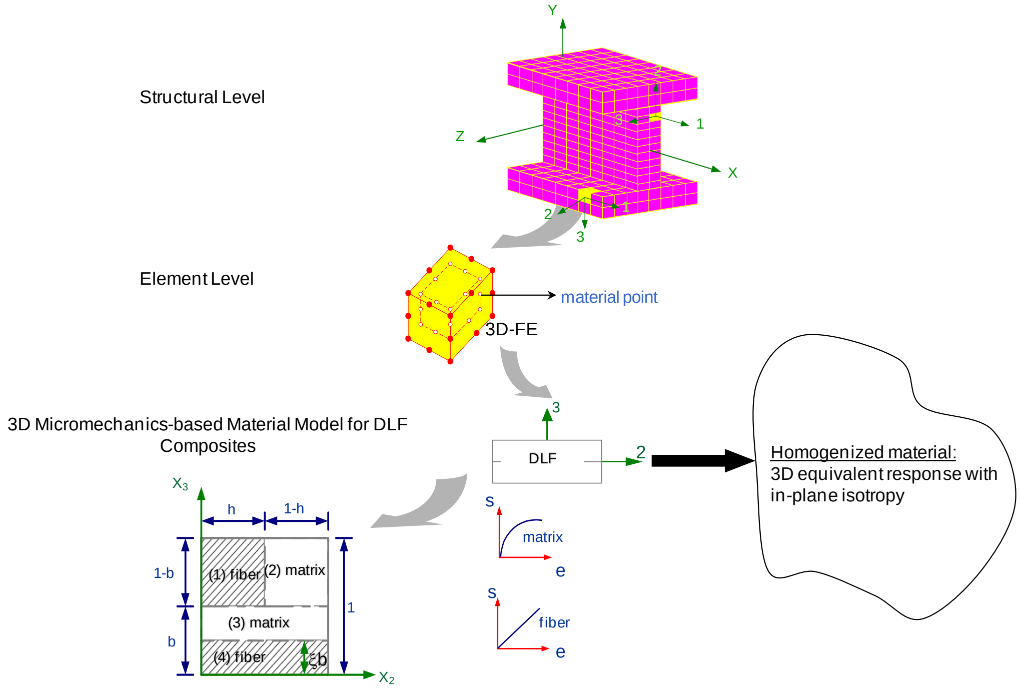

Figure 2. Nested micromechanical and structural framework.

The structural framework is generated by applying the developed micromechanical model within a 3D FE formulation in order to form a global-local nonlinear analysis of DLF structures. The material subroutine (UMAT) of the ABAQUS FE code is used to implement the nonlinear micromechanical model. This subroutine operates at each integration point and its task is to update the stress, stiffness, and history variables, for a given strain increment. For finite strain increments and nonlinear material response, the tangential stresses and strains typically violate the nonlinear constitutive relations of the sub-cell materials. In order to satisfy the actual stress-strain relationships as well as the traction and compatibility constraints, a correction scheme is needed. Therefore, a stress update algorithm is developed which consists of two steps: (1) a predictor step, which may be a tangential or a trial elastic predictor; followed by (2) a correction step, in which the trial elastic state is adjusted in order to arrive at accurate stress values. Using a predictor step alone, without subsequent correction, may lead to unacceptable accumulation of error. This makes the task of efficient numerical implementation of the proposed micromodel very important in order to perform nonlinear analysis of realistic DLF composite structures.

3. Micromechanical model for the DLF composite system

The DLF material is considered as a medium where resin is reinforced with flakes randomly distributed in the plane of the layer. Therefore, the DLF effective medium can be represented with an in-plane isotropic model. The DLF UC model generates 3D equivalent response with in-plane isotropy for the DLF medium by a weighted average of two UC models (Figure 3). The first is a matrix-mode layer (transverse), which is modeled using a UC where the fibers are completely surrounded by a matrix phase. The second is a model for a fiber-mode layer, in which the fibers are not shielded by the matrix, and both constituents have the same average strains.

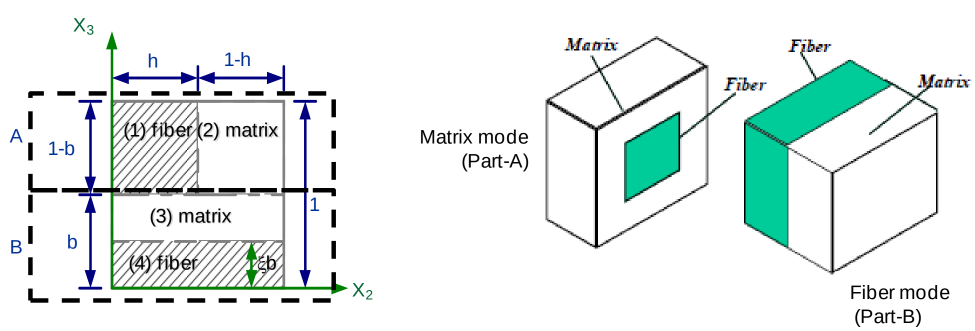

Figure 3. DLF unit cell.

The DLF UC model is shown in Figure 3 as a collection of four sub-cells. It is also constructive to note that the matrix-mode layer (part A) is composed of sub-cells (1) and (2), while the fiber-mode layer (part B) is composed of sub-cells (3) and (4). The out-of-plane direction is represented by axis 3. The spatial variation of the displacement field in each sub-cell is assumed such that the stresses and deformations are spatially uniform. Traction continuity at an interface between sub-cells can therefore be satisfied only in an average sense. The 3D stress-strain constitutive characterization for the fiber and matrix constituents is performed at the lowest level of the nested modeling framework. In the current study, the fiber is modeled as a linear material and the matrix constituent is modeled as a nonlinear material.

The DLF micromodel is driven by the in-situ response of its fiber and matrix constituents (sub-cells). In this study, those are the properties of the AS4 carbon fiber and the PEEK resin. V-notch in-plane shear test results are used to calibrate the micromodel in the linear stress-strain range. The nonlinear material response of the composite is attributed to the matrix and it is modeled using the J2- deformation theory along with the Ramberg-Osgood (R-O) nonlinear uniaxial representation. The in-plane shear test results are also used to calibrate the nonlinear matrix behavior. The R-O stress-strain for the matrix is calibrated by varying its parameters until the overall nonlinear response for the composite is matched with the V-notch test results. The calibration of the model is concluded with finding the three R-O parameters.

4. Prediction of the DLF elastic properties and stress-strain behavior

The prediction capability of the micromodel for DLF composites is examined for coupons that are subject to in-plane tension and compression and out-of-plane shear loading. These tests were performed in displacement control mode in order to reach the ultimate load and a complete breakage of the coupon. Strain gages were used to monitor the strains at the center of the coupons.

The ratios of computed effective moduli and Poisson's ratios to the experimentally obtained ones for the DLF material are reported in Table 1. Experimental values are the average of the test results performed at room temperature. The predicted values from the present micromodel compare favorably with those obtained experimentally.

Table 1. Ratio of predicted to experimentally obtained effective elastic properties.

Property	E_{11}	E_{22}	G_{13}	G_{23}	ν_{12}
Predicted/Test	1.00	1.00	0.99	0.99	0.90

Figure 4 shows the experimental stress-strain curves (with repeated tests) and the prediction of the model (solid line) for out-plane shear behavior. The stress-strain curves are plotted as the stress, monitored from the load cell of the machine, against the strain gage readings. The predicted result from the micromodel is in excellent agreement with the test results. These results demonstrate the ability of the proposed nonlinear micromodeling formulation to capture the nonlinear behavior of DLF material.

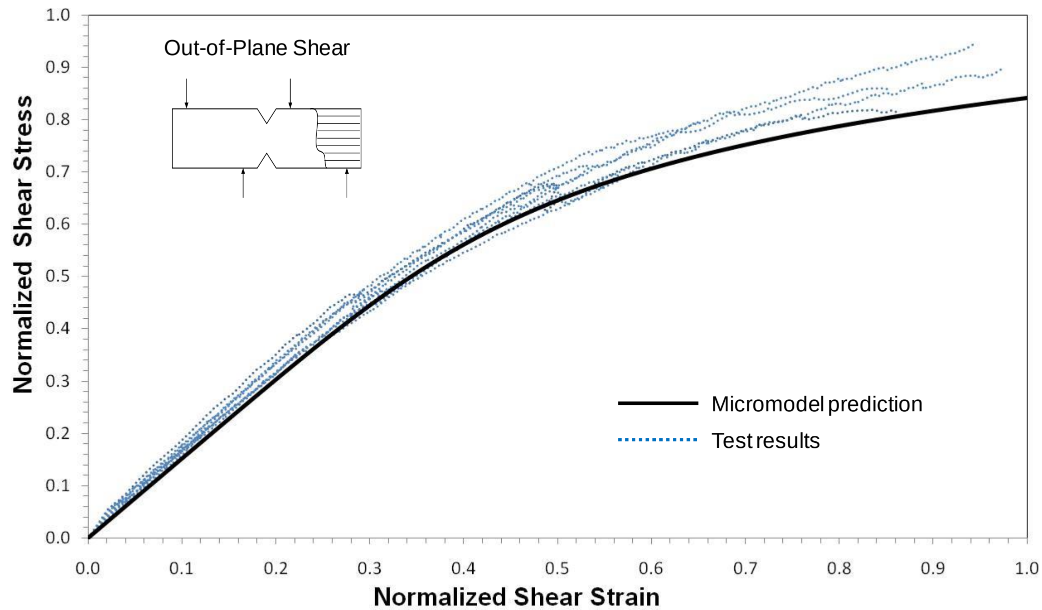

Figure 4. Predicted and experimental nonlinear out-of-plane shear stress-strain behavior of DLF material.

5. Progressive damage analysis

Progressive damage modeling is very important because it allows for the simulation of degraded structural responses, especially when the structure can continue resisting additional applied loads despite failure at limited locations. The first step in the damage analysis is to establish a suitable failure criterion for damage initiation in the material. Then, the effective elastic properties for composite material have to be degraded gradually or are set to a small number for the composite material. In the case of micromechanics-based modeling, progressive damage methodology can be applied at the constituent level.

To that end, 3D Tsai-Wu failure criterion is used to detect damage initiation in the DLF material. The criterion represents a general quadratic failure surface in the stress space. Both the in-plane and out-of-plane modes of failure are considered in this study. Ultimate stress values required to establish the 3D Tsai-Wu failure criterion are obtained from the coupon tests.

A damage index, F, is introduced as the maximum value of the Tsai-Wu failure criterion that an integration point has experienced during all loading states. Damage index contours are used to show the progression of damage in the structure. When F is larger than 1 at an integration point, it means that the Tsai-Wu failure criterion has been exceeded and the progressive damage formulation is active. Once damage is detected, the contribution of fiber sub-cells to the effective properties of DLF composite material is set very close to zero. The reason to apply this methodology is because damage initiates and propagates between the boundaries of DLF flakes in the material where the fibers are not continuous. The elastic and nonlinear properties of matrix sub-cells are degraded gradually at the damaged areas.

Another progressive damage analysis approach is also considered in this study. Instead of degrading the constituent properties at the micromechanics-level, stiffness of a damaged element is not taken into account in the global stiffness matrix. The new “element deletion control by state variables” functionality in Abaqus/Standard version 6.14 is employed to perform this type of progressive damage analysis approach. An additional state variable is assigned in the user material subroutine to deactivate the material point when the damage index F is larger than 1 for the 3D Tsai-Wu failure criterion.

6. Nonlinear and progressive damage analysis of DLF composite plate under four-point bending load

The micromechanical and structural framework is used to predict the performance of a DLF plate under four-point bending load as seen in Figure 5. Both of the proposed progressive damage approaches, micromechanics-level and element deletion, are also used in the FE analysis. An FE model with quarter symmetric boundary conditions is developed to represent the actual conditions of the testing. Interactions are used at the loading and support pin locations. Kinematic coupling is used to apply the displacement to the loading pin.

The predicted part performances using the 3D nonlinear micromodel along with the micromechanics-level and element deletion progressive damage approaches are compared with the experimental results as shown in Figure 6. Load and displacement values in Figure 6 are obtained at the center of the loading fixture. As seen in Figure 6, good agreement is shown when comparing the experimental results and the FE model that incorporates the combined micromechanical and progressive damage approaches. In the case of using the 3D nonlinear micromodel along with the micromechanics-level damage approach, the predicted ultimate load is the last point before the failure point (larger red circle) on the predicted load-displacement curve in Figure 6. The predicted ultimate load, from the FE model, is very close to the average of the experimental results.

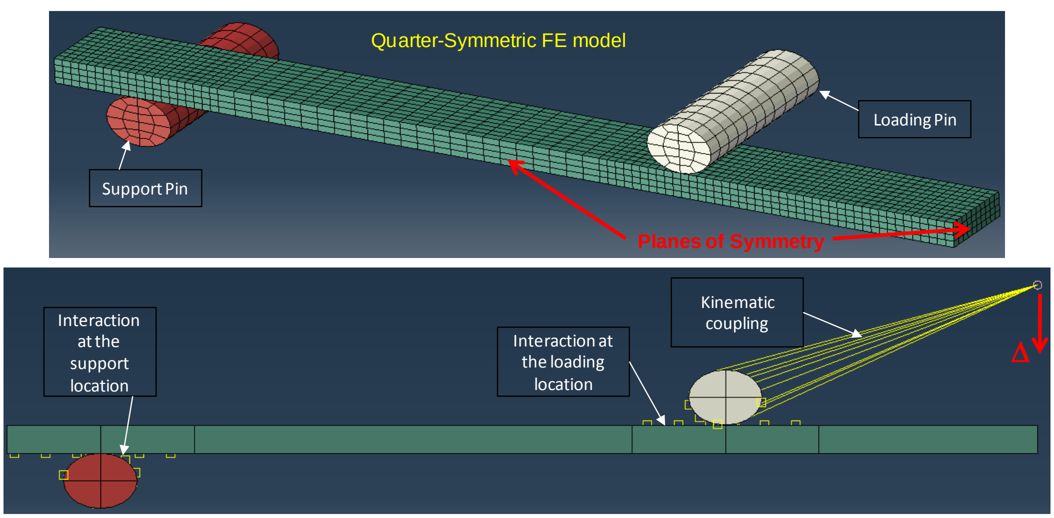

Figure 5. Quarter-symmetric FE model for four-point bending DLF plate.

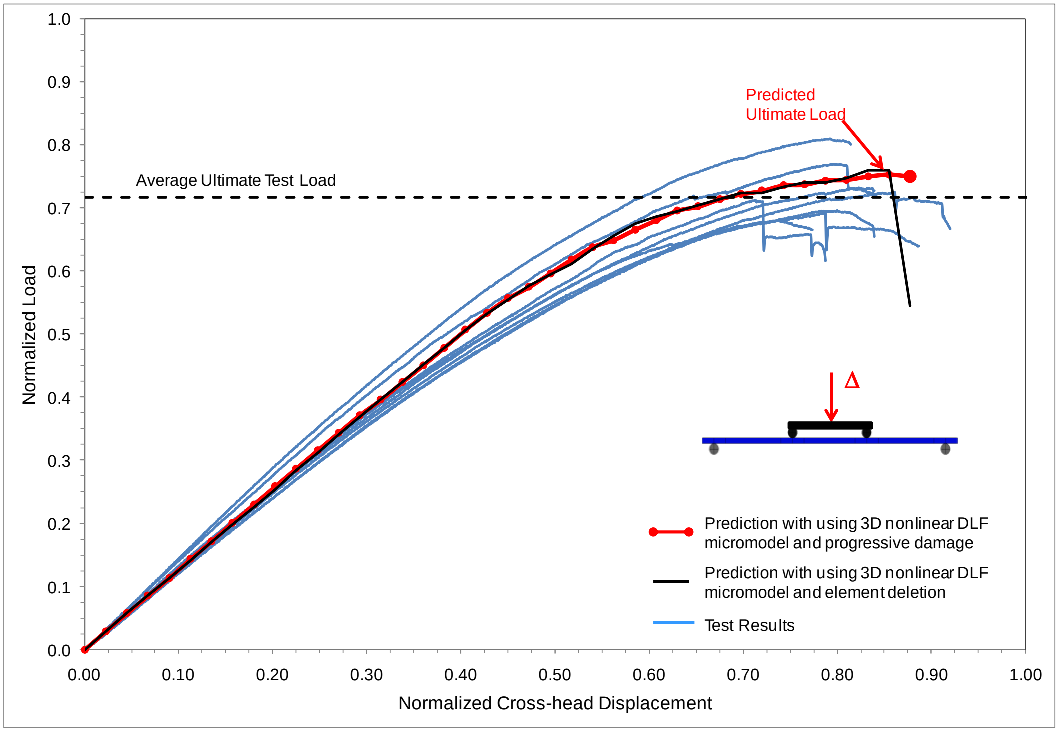

Figure 6. Predicted and experimental response of four-point bending plate.

First failure load is predicted to occur at the normalized load of 0.507 at which the damage index value for the 3D Tsai-Wu failure criterion exceeds 1for the first time. First failure occurs in the outermost layers in tension because the uniaxial tensile strength of the DLF material is lower than the uniaxial compression strength.

7. Nonlinear and progressive damage analysis of DLF composite T-beam under four-point bending load

The micromechanical and structural framework is also used to predict the performance of a DLF T-beam part under four-point bending load, as shown in Figure 7. An FE model with quarter-symmetric boundary conditions is developed to represent the actual conditions of the part testing. The proposed progressive damage approach at micromechanics-level is also employed in the FE analysis. Material directions are selected such that the out-of-plane direction is always normal to the surfaces including the fillet area. Flow of the material can also be seen in the CT-scan image of a T-beam cross-section. Loading and support pins are modeled using hexagonal and tetrahedral elements, respectively. Hexagonal elements are used to model the DLF T-beam. Kinematic coupling is used to apply the displacement to the loading pin.

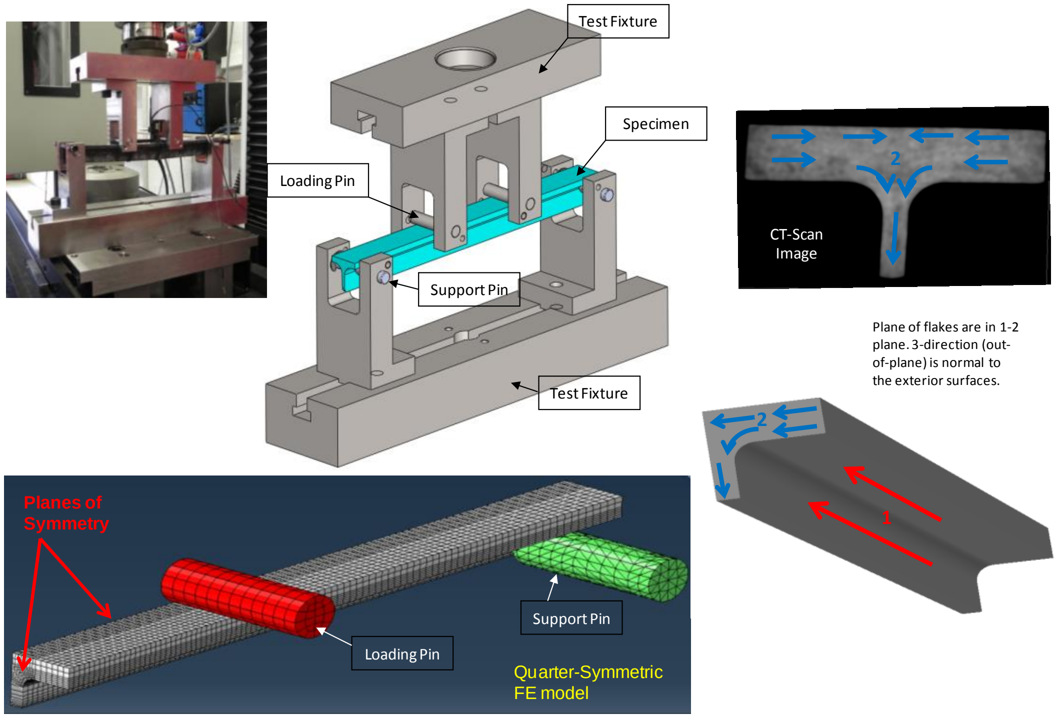

Figure 7. Quarter-symmetric FE model for DLF T-beam.

Two different geometries are considered for the nonlinear and progressive damage analysis of DLF T-beams. First geometry has a larger fillet radius and thinner web thickness than the second one as shown in Figures 8 and 9.

The predicted and experimentally obtained part performances are compared with each other in Figures 8 and 9. Good agreement is shown when comparing the experimental load-displacement results and the predicted ones from the FE model that incorporates the combined micromechanical and progressive damage models. The predicted ultimate loads are the last points on the predicted load-displacement curves. The predicted ultimate load values from the FE model are very close to the average values of the experimental results.

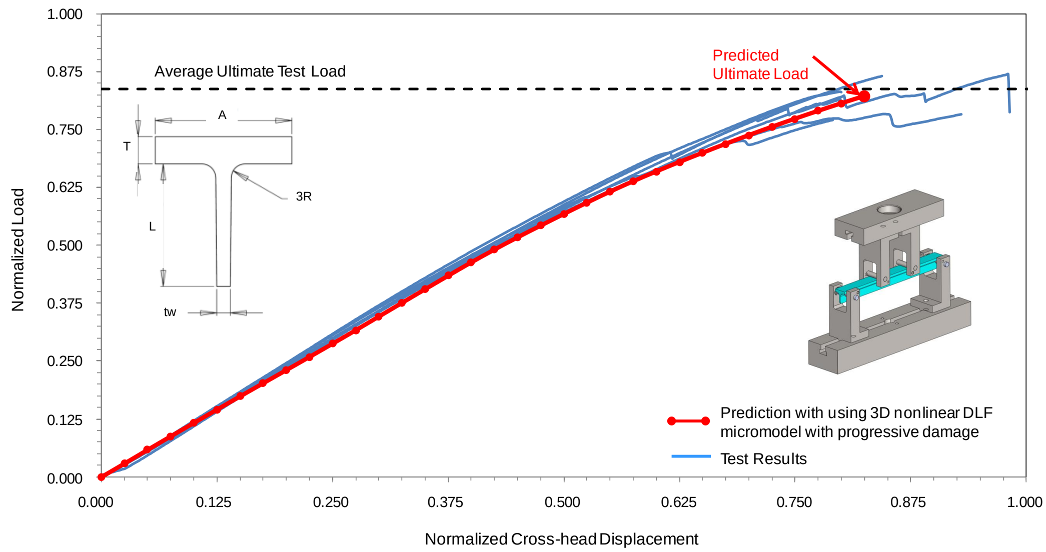

Figure 8. Predicted response of T-beam using the DLF micromodel and progressive damage approach – configuration 1.

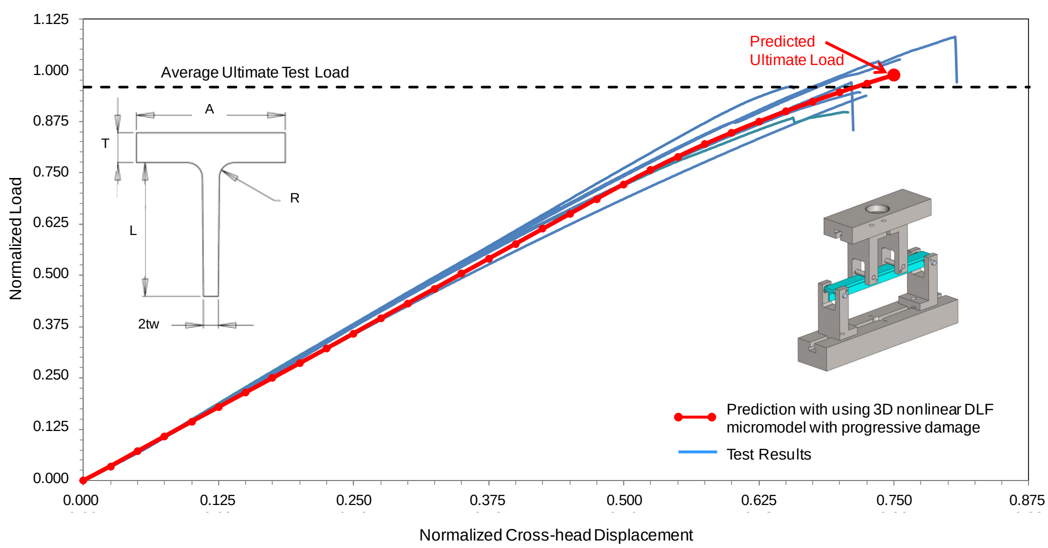

Figure 9. Predicted response of T-beam using the DLF micromodel and progressive damage approach – configuration 2.

8. Comparison of predicted and experimentally obtained damage locations for DLF angle bracket

The micromechanical and structural framework along with the micromechanics-level progressive damage approach is also used to predict the performance of a DLF angle bracket part. Twenty-nine parts were tested under the loading condition shown in Figure 10. Each part was attached to the steel loading arm and base plate using steel bolts. An FE model with symmetric boundary conditions is developed to represent the actual conditions of the part testing.

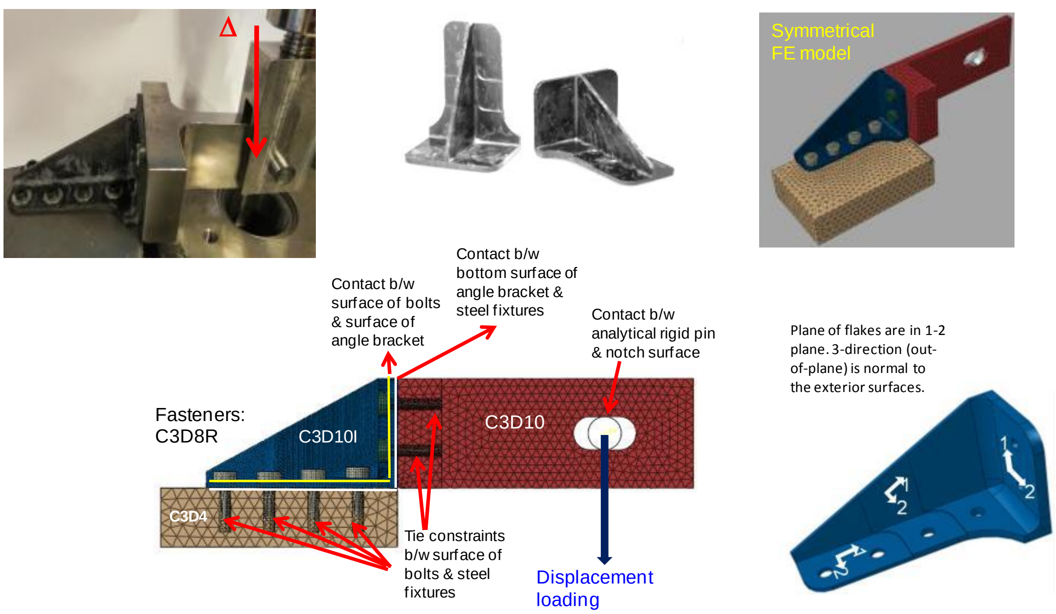

Figure 10. FE model for the DLF angle bracket.

Figure 11 shows the comparison of the predicted damage locations in the DLF part with the damage seen at the end of the part testing. Gray areas in the FE contour plots are the predicted damaged areas where the damage index value for the 3D Tsai-Wu failure criterion exceeds 1. Good agreement is shown when comparing the experimental results and the FE model predictions for the damage locations in the DLF part.

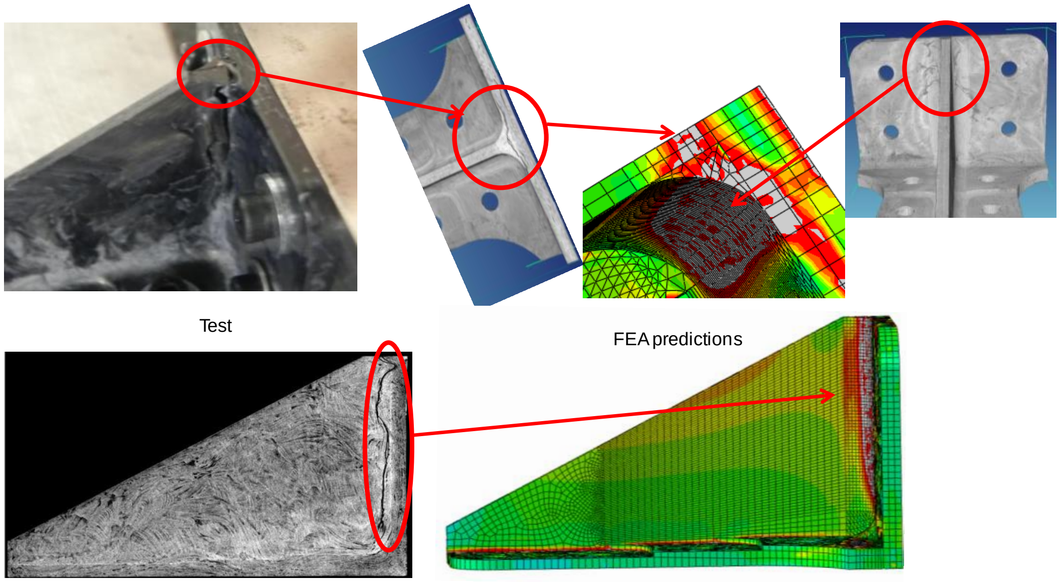

Figure 11. Predicted and experimentally obtained damage locations for the DLF angle bracket.

9. Conclusions

An effective integration of micromechanical and structural framework is formulated for the nonlinear analysis of DLF composite materials and structures. The DLF micromodel explicitly recognizes the response of the fiber and matrix constituents at the lower level of hierarchy in the framework. The developed model predicts the overall nonlinear behavior of DLF composite material under a general multi-axial state of loading. Coupon tests are used to experimentally verify the predicted stress-strain behavior using the micromodel. The DLF micromodel demonstrates good prediction capabilities for the effective properties and multi-axial nonlinear behavior of DLF composites.

The framework is easily incorporated within a classical displacement-based FE structural modeling using 3D continuum elements and additional stress correction algorithm. A damage modeling approach is also integrated with the micromechanical model to form a framework for the progressive damage analysis of DLF composite structures. The new "element deletion control by state variables" functionality in Abaqus/Standard version 6.14 is also employed to perform another type of progressive damage analysis approach. The modeling approaches are applied to DLF composite parts made up from an AS4/PEEK material system. Ultimate (failure) loads are predicted by the framework for different DLF composite parts. Contours of the attained maximum value of the 3D Tsai-Wu criterion are plotted for the DLF parts to indicate the damage progression. The framework shows very good predictive capabilities for the overall effective properties, nonlinear response, and ultimate load of DLF composites.

10. References

1. Greene, T., “Discontinuous Long Fiber Composites for Complex Shape Metal Replacement,” CAMX 2014 Conference Proceedings, Orlando, FL, June 2-5, CAMX – The Composites and Advanced Materials Expo, CD-ROM-13 pp, 2014.

11. Acknowledgements

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