Delamination and damage progression in a composite laminate subjected to bending using multicontinuum theory

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Delamination and damage progression in a composite laminate subjected to bending using multicontinuum theory

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Multiscale nonlinear progressive failure analysis of a composite laminate experiencing delamination as a primary failure mode is studied using multicontinuum theory (MCT). The analysis treats the fiber and matrix constituents of a composite lamina as separate but linked constituents. Fiber failure and matrix failure, including delamination, are modeled independently using stress-based failure criteria formulated in terms of constituent stresses generated through the MCT decomposition. Several variations of modeling the post-failure response of the constituents are investigated.

Comparisons of experimental and analytical load-deflection curves are generally excellent. The results suggest the MCT analysis, coupled with nonlinear damage progression in a finite element setting, is capable of modeling delamination as a primary failure mode. A comparison of element formulations involving 3-D elements and layered solid and shell elements is also presented. Results indicate there is a trade-off in accuracy and computational speed when using layered elements compared with 3-D elements modeling each ply individually.

Introduction

Ultimate failure of composite structures is an extremely complex event. Multiple local damage mechanisms often initiate at loads far below structural failure. Damage mechanisms may include submicrocrack (void) accumulation in the matrix, macroscopic matrix cracks, fiber rupture in tension, fiber kinking or crushing in compression, and delamination between plies. Delamination is of particular concern to many applications where understanding survivability or airworthiness is a requirement. The tendency for a delamination to grow rapidly and in an unstable manner increases the need for high fidelity simulation capabilities to evaluate the likelihood and consequence of a delamination event.

Multiscale analysis provides a unique way to view delamination. Rather than treating the delamination as a discrete fracture, using multiscale analysis it is treated simply as a failure mode that occurs in the matrix constituent. Using matrix constituent stresses to predict failure and degrading matrix stiffness after a failure event is realized removes the need for prior knowledge of the delamination location and reduces the need for model inputs to aerospace industry standard lamina material properties.

A practical approach to multiscale composite failure analysis is multicontinuum theory (MCT) as introduced by Mayes and Hansen [1]. MCT represents an extension of the continuum hypothesis for a continuous fiber unidirectional lamina by treating the fibers and matrix as separate but linked continua. Thus, constituent stress and strain fields are efficiently produced in the course of a routine structural analysis.

The term “constituent stress/strain field” is important to understand in the context of an MCT analysis. The fundamental premise underlying continuum mechanics is that all mathematical variables represent average values of the quantity of interest. The concept of a multicontinuum simply extends the notion of a continuum to reflect coexisting materials within a material point. Hence, constituent stress/strain fields represent continuum (phase averaged) fields that are exactly analogous to their single continuum counterparts.

The ability to access constituent level stress or strain fields opens an exciting window into composite material behavior as *constituent* failure mechanisms may be identified and linked to their respective *constituent* stress and strain fields. Mayes and Hansen [1, 2] followed this approach by proposing quadratic interactive constituent failure criteria based on the constituent stress fields. An important feature of the constituent failure criteria is that they are fully three-dimensional. Although many composite structural applications involve plane stress, even the simplest of one-dimensional loads in a composite laminate induces three-dimensional stress states in the constituents of any ply. It is imperative to account for out-of-plane stresses in any constituent-based failure theory. Moreover, the failure criteria need not be altered to accommodate fully three-dimensional *structural* stress states.

The MCT failure theory has been benchmarked against hundreds of experimental results since its inception. These include structures ranging from coupon-level tests to massive structures such as an Interstage Adapter built for the Atlas V launch platform and tested at the US Air Force Research Laboratory [3]. The loading scenarios for coupon-level tests have been primarily in-plane, or three-dimensional cases with large hydrostatic stress states. In this article, MCT multiscale analysis is coupled with stress based failure criteria to predict delamination onset and propagation within a composite lamina using only industry standard composite lamina inputs.

Multicontinuum Theory

Consider a "material point" located within a ply of a composite laminate. The continuum hypothesis assumes the stress or strain field at this point represents an average value of a material volume whose physical dimensions are small compared to the physical dimensions of the laminate, yet large enough to represent the microstructure of the material. Hence, in the case of a continuous fiber unidirectional ply, a material point must represent the characteristics of a volume large enough to contain numerous fibers and the surrounding matrix as shown in Figure 1 (a). The macroscopic value used to characterize the stress tensor at a point in the continuum is given by the volume average of the micro-stress field of the material point.

The material point of Figure 1(a) is comprised of two clearly identifiable constituents with drastically different material properties. Hence, a natural extension of the continuum hypothesis is to treat the material as a multicontinuum consisting of two interacting continua comprised of fibers (*f*) and matrix (*m*) as shown in Figure 1(b) and Figure 1(c). Definitions for constituent stress fields may then be introduced as the volume average of the stresses in the fiber and matrix, respectively.

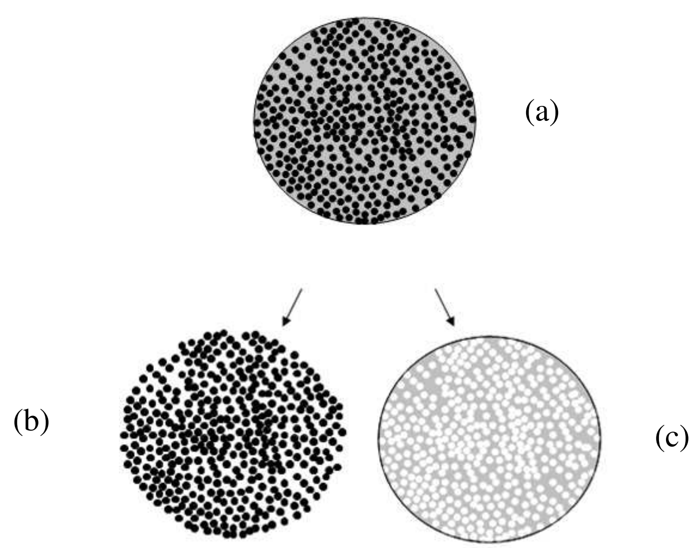

Figure 1. Schematic of a multi-continuum decomposition showing: (a) a continuum point for a unidirectional composite lamina, (b) a continuum point for the fibers only, and (c) a continuum point for the matrix material.

Knowledge of the constituent material properties and those of the composite provide the necessary information to mathematically link the continua of Figure 1. Given the material properties of the constituents, the material properties of the composite are established through a finite element micromechanics analysis. Here-in lies another distinguishing feature of MCT in that any geometric microstructure may be used to establish the composite material properties, including a random microstructure that is representative of the microstructure of Figure 1(a). Moreover, there is no computational penalty associated with modeling complex microstructures as all micromechanics analyses are conducted prior to structural analysis. The decoupling of the micromechanics and structural solutions is enforced in nonlinear problems as well, as composite properties may be related to constituent properties through simple curves, even for the case of complex orthotropic matrix material degradation schemes (Kenik [4]).

Given a composite stress and strain field, and assuming linear elastic behavior in an incremental loading scheme, it is a straightforward matter to decompose the composite fields down to the constituent stress/strain fields for the fiber and the matrix. The decomposition is attributed to Hill [5] and a detailed development for thermoelastic problems may be found in Mayes and Hansen [2]. Garnich and Hansen [6] provide an algorithm for viscoelastic composites consisting of linear elastic fibers with a linear viscoelastic matrix.

Motivation for implementing an MCT analysis lies in the simple fact that composite state variables such as stress and strain mask the state variables of the constituents. Moreover, the constituent state variables drive the localized damage within the constituents. Numerous examples of composites masking constituent behavior have been presented in the literature. Examples include purely mechanical problems, thermo-mechanical problems, and interesting viscoelastic phenomena.

Perhaps the simplest and most elegant example of composites masking constituent behavior is that of free thermal expansion/contraction of a unidirectional composite. As an unconstrained unidirectional composite is cooled, the composite stress field is identically zero. However, large self-equilibrating thermally induced stresses are generated in both the fiber and matrix constituents. Matrix stresses generated during cooling to cryogenic temperatures may be of significant magnitude to cause matrix cracking (Dalgarno [7]). An MCT analysis faithfully reproduces these constituent stresses and, most importantly, does so in the context of a structural analysis. For instance, the constituent thermal phenomena associated with the free thermal contraction problem of a unidirectional composite may be captured in a finite element model using a single element.

Constituent Failure Criteria

Simple quadratic stress-based failure criteria (Eqs. 1-2), expressed in terms of transversely isotropic stress invariants of the constituents (Eqs. 3), are used to predict constituent failure within a lamina.

$$ {}^{\pm}A_{1f} I_{1f}^2 + A_{4f} I_{4f} = 1 \,, \tag{1} $$

$$ {}^{\pm}A_{1m} I_{1m}^2 - {}^{\pm}A_{2m} I_{2m}^2 + A_{3m} I_{3m} + A_{4m} I_{4m} - {}^{\pm}A_{5m} I_{1m} I_{2m} = 1 \quad , \tag{2} $$

where

$$ \begin{aligned} I_1 &= \sigma_{11} \,, \\ I_2 &= \sigma_{22} + \sigma_{33} \,, \\ I_3 &= \sigma_{22}^2 + \sigma_{33}^2 + 2\sigma_{23}^2 \,, \\ I_4 &= \sigma_{12}^2 + \sigma_{13}^2 \quad . \end{aligned} \tag{3} $$

In the above, the $I_{i\beta}$ terms denote transversely isotropic stress invariants for each constituent, $\beta=f$ for fiber, $\beta=m$ for matrix. The coefficients A_{jf} and A_{jm}, leading the invariants, are constituent failure parameters derived from experimentally determined composite ultimate strength data through correlation with the MCT decomposition.

Motivation for the fiber failure criterion may be found in Mayes and Hansen [2]. The matrix failure criterion is an extension of a von Mises criterion to accommodate transversely isotropic materials. Functionally, the criterion is similar in form to those proposed by Hashin [8] or Tsai-Wu [9] for unidirectional composite materials. However, a fundamental difference in this instance is that the MCT failure criterion of Eqn. 2 applies to the matrix constituent. Note that the matrix must be treated as transversely isotropic in failure due to the geometric anisotropy introduced through microstructure. Specifically, if the fibers of a unidirectional composite are removed, the remaining matrix is a continuum with holes as shown in Figure 1(c). One can envision that the failure of this matrix is not isotropic. In the work herein, it is assumed that a delamination in a matrix event and is governed by the matrix failure criteria.

Progressive Failure Analysis

An important aspect of composite failure simulation is accurately representing the progressive nature of constituent damage leading to ultimate failure. Success here requires crossing multiple geometric scales to capture where local damage initiates while delivering meaningful information on the structural response to the analyst.

A multiscale MCT analysis begins by using nonlinear finite element analysis to bring stress-strain resolution down to the lamina level. Embedded in the finite element analysis is the MCT decomposition that decomposes ply level stress/strain fields down to the constituent level of the fiber and matrix. A variety of nonlinear deformation mechanisms introduce inelastic behaviour, particularly in the matrix constituent.

A key element of modelling nonlinear behavior in the matrix is appropriately degrading matrix material properties after damage is predicted. This stiffness degradation drives the stress redistribution that leads to failure propagation in a structure and its ultimate failure.

Two fundamentally different matrix material degradation schemes have been implemented within an MCT analysis. Mayes and Hansen [2] used a remarkably simple approach where, when matrix failure was detected, the subsequent matrix properties were instantaneously degraded to a fraction of their original value, thereby assuming the matrix immediately loses its load carrying capacity. While this approach worked well for unidirectional laminates, the method produced overly conservative results in multidirectional laminates for load cases where matrix failure was largely responsible for ultimate failure of the laminate.

An alternate approach to the discrete reduction of matrix properties is to introduce a post-failure response where matrix properties are gradually degraded with increasing deformation. Physically, a gradual degradation in matrix behavior is seen in some laminates because matrix damage is highly localized and load redistribution through complex load paths involving adjacent plies allows the matrix to sustain load a short distance away from the local failure. Knops and Bögle [10] clearly demonstrate a laminate effect producing gradual material degradation in the matrix. Kenik [4] used a post-failure orthotropic matrix response in MCT analyses of multidirectional composite laminates.

Although the latter approach of a gradual post-failure matrix response is intuitively more accurate, there are compelling computational reasons to consider the original approach of instantly degrading the matrix properties. First, the approach is considerably more computationally efficient in a finite element environment. Moreover, in cases where ultimate failure is fiber dominated, the two approaches often produce very comparable results. While both forms of matrix degradation are explored in the present work to delineate differences in the two approaches, the emphasis is placed on the simpler form of instantaneous degradation. Justification for this choice is that the failure modes considered here-in are primarily due to delamination and fiber rupture, both of which are largely independent of the form of matrix degradation.

In contrast to matrix failure, failure of the fiber constituent is always treated as being instantaneous. Fibers are assumed linear elastic prior to failure. When fiber failure is detected, specific fiber properties are instantaneously set to near zero values and loads are allowed to redistribute to adjacent plies within the laminate.

In what follows, we present details of the material degradation model based on instantly degrading the matrix properties. The discussion uses nomenclature found in Tsai [11]. Composite laminae are modelled with three distinct material states. Degraded ply properties are calculated using finite element micromechanics analyses with reduced constituent stiffness values. Let E_m* denote the percentage of original matrix stiffness and E_f* denote the percentage of original fiber stiffness. Material state 1 represents an undamaged composite. Material state 2 is defined as undamaged fibers with matrix degradation of $E_m^* = 10\%$. The degradation value of 10% is motivated by experimental data provided by Knops and Bögle [10]. Note here that both Young's modulus and the shear modulus are degraded by E_m*. Poisson's ratio is assumed to remain constant. Material state 3 uses the same degradation scheme of $E_m^* = G_m^* = 10\%$ for the matrix and applies a degradation of $E_f^*=0.1\%$ to the longitudinal direction of the fibers. All other fiber elastic constants are unaltered as a fiber rupture is assumed to only affect longitudinal behavior. However, because both fiber and matrix properties have been degraded as described, material state 3 simulates complete failure of a lamina. Fiber degradation schemes have seen little attention in the literature compared to matrix degradation models and we believe this area of research is worthy of further attention.

Prior to the finite element structural analysis, composite elastic constants for each material state are determined from micromechanics and stored to eliminate the need for the micromechanics model in a nonlinear progressive failure analysis.

Experimental Summary

The damage progression of a composite laminate subjected to a three-point bend experiment was reported by Tay, *et al.* [12]. In this work, three graphite-epoxy cross-ply laminate specimens were tested. The lay-up used was $[0_3/90_3/0_3/90_3/0_3]$, with the 0° direction coinciding with the span between supports. Specimens averaged 2.14 mm in thickness with a width of 25 mm. Each specimen was simply supported on cylindrical rollers 60 mm apart. The displacement controlled load was applied through a cylindrical roller at the midspan. A rubber pad was placed between the roller and the beam to prevent premature local crushing. For modeling purposes, Tay *et al.* [12] estimated that the contact zone of the rubber pad was approximately 5mm.

During testing, the following damage sequence occurred in a rapid progression. For clarity, we refer to five distinct layers consisting of three 0^o layers and two 90^o layers with layers ordered sequentially from top to bottom. Initially, localized crushing in the first 0° layer occurred near the point of load application at approximately a load of 1.94 kN. Next, a delamination formed and grew at the first 0^o-90^o interface between the first and second layers. This delamination was rapidly followed by a second delamination between the third (0°) and forth (90°) layers. After the second delamination propagated some distance away from the load, it kinks through the forth layer (90°) and continued along the interface with the fifth layer (0°). Ultimate failure of the specimen rapidly followed this event. Tay *et. al.* [12] reported that the damage pattern was quite consistent between all specimens. A photograph showing various damage mechanisms occurring during testing is shown in Figure 2.

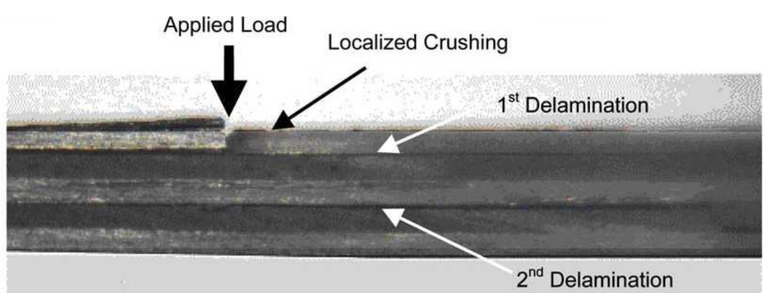

Figure 2. Failure pattern observed in the experimental specimen.

Progressive Failure Modeling Strategy

A finite element model of the specimen was created using Abaqus/Standard with the MCT analysis embedded as a user-defined module. By exploiting symmetry, only half of the beam is modeled. One three-dimensional element was used to represent the in-plane direction (width) of the beam. Appropriate boundary conditions were applied to the nodes on the in-plane faces to enforce a plane strain condition. The simple supports were modeled with nodal constraints and the load head is modeled as a rubber block. Five reduced integration solid elements (C3D8R) are used to represent the thickness of each material layer to ensure local stress resolution at ply boundaries was converged. Matrix and fiber properties are degraded instantaneously to values defined in the previous section. In the following sections, this model is referred to as the "baseline model."

Elastic constants for the fiber and matrix constituents, as well as a unidirectional carbon/epoxy ply with a 60 % fiber volume fraction, are provided in Table 1. Transverse isotropy is assumed with the fiber direction taken as x_1. Failure strengths for the unidirectional carbon/epoxy are also presented in Table 1.

Table 1. Elastic constants and strengths for: IM7/977-3 carbon/epoxy unidirectional lamina with a 60% fiber volume fraction, and elastic constants for (a) IM7 carbon fiber, (b) 977-3 epoxy matrix.

IM7/977-3 Transversely Isotropic Composite Material Properties with 60% Fiber Volume Fraction

E_{11} (*GPa*)	E_{22} (*GPa*)	ν_{12}	ν_{23}	G_{12} (*GPa*)	G_{23} (*GPa*)
161	8.3	0.24	0.33	5.3	3.1

IM7/977-3 Transversely Isotropic Composite Strengths with 60% Fiber Volume Fraction

$+S_{11}$ (*GPa*)	$-S_{11}$ *GPa*)	$+S_{22}$ (*MPa*)	$-S_{22}$ (*MPa*)	S_{12} (*MPa*)	S_{23} (*MPa*)
2.63	-1.68	84.0	-281.0	82.0	155.0

In-Situ IM7 Carbon Fiber Properties

E_{11} (*GPa*)	E_{22} (*GPa*)	ν_{12}	ν_{23}	G_{12} (*MPa*)	G_{23} (*MPa*)
267	14	0.185	0.1	9.4	6.6

In-Situ 977-3 Matrix Material Properties

E_{11} (*GPa*)	E_{22} (*GPa*)	ν_{12}	ν_{23}	G_{12} (*MPa*)	G_{23} (*MPa*)
3.8	3.8	0.34	0.34	1.4	1.4

Damage Progression in a Three-point Bend Specimen: Results and Discussion

Baseline Solution

Figure 3 shows an experimental load versus displacement curve compared to MCT analytical predictions using the baseline model. The experimental curve shows some distinct nonlinearity on initial load-up that is not captured by the analytical model. We believe this response is due to material nonlinear behavior found in the rubber pads as well as geometric nonlinearity which was not modeled in the analysis. The load-displacement plot recorded during the experiment shows a maximum load of 1.94 kN is reached followed by two discrete failure events. Immediately after the first failure event, a distinct load reduction of 1.14 kN is observed in the displacement controlled test. Continued loading begins from 0.8 kN and increases to 1.1 kN where a second failure event is observed. A load reduction of 1 kN follows the second failure event. Continued deformation after the second event shows little ability for the specimen to sustain additional load.

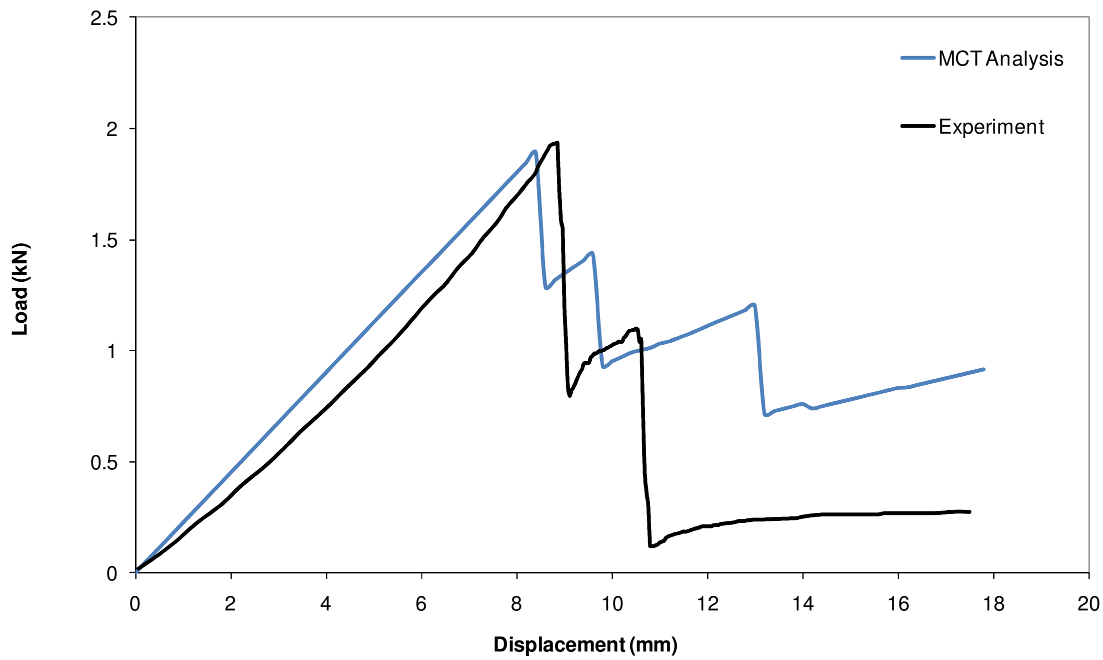

Figure 3. Load-displacement comparison of the baseline MCT model predictions and the experimental results.

Analytical predictions of the first failure event are exceptional as the predicted load of 1.89 kN is within 2.5% of the experimental result. Also captured in the analytical prediction is the load drop off behavior; however the magnitude of the drop off is approximately half of the drop off seen in the experiment. We believe the experimental load drop is due to both material failure and delamination. The material property degradation model used in the analysis only reduces element stiffness and is not capable of capturing the discrete opening behavior caused by a delamination.

The analysis shows reloading after the first failure event takes place at a slope very similar to the experiment data. Moreover, the analysis predicts a second failure event and subsequent load drop-off. Again, the magnitude of the load drop off is approximately half that observed in the experimental load-deflection curve.

Tay *et al.* [12] reported the first observed damage event is local crushing of the first 0° layer near the point of the load application and the growth of the first delamination at the interface between the first (0°) and second (90°) layers as shown in Figure 2. Damage predictions provided by MCT are shown in Figures 4 (a-d). Figure 4(a) clearly shows failure of fiber and matrix in the first 0° layer near the point of the load application, occurring immediately after the first discrete failure event is predicted (load displacement: δ=8.4 mm). Figure 4(b) shows the analysis predicts matrix failure propagation along the interface between the first (0°) and second (90°) layers. The matrix failure correlates well with observed delamination between these layers. Figure 4(c) shows predicted damage immediately after the second failure event. Fiber failure is observed in the first and third layers (0°) layers and matrix failure is predicted in the second layer (90°). Unlike the experimental load-deflection curve, the MCT analysis shows a third distinct failure event at a displacement of 14.8 mm. Figure 4(d) shows damage after the third failure event. Fiber failure is observed in all 0° layers and matrix failure is observed in all 90° layers. The beam again begins loading after the third failure event, but in practice, one has pushed the analysis far beyond ultimate failure of the structure.

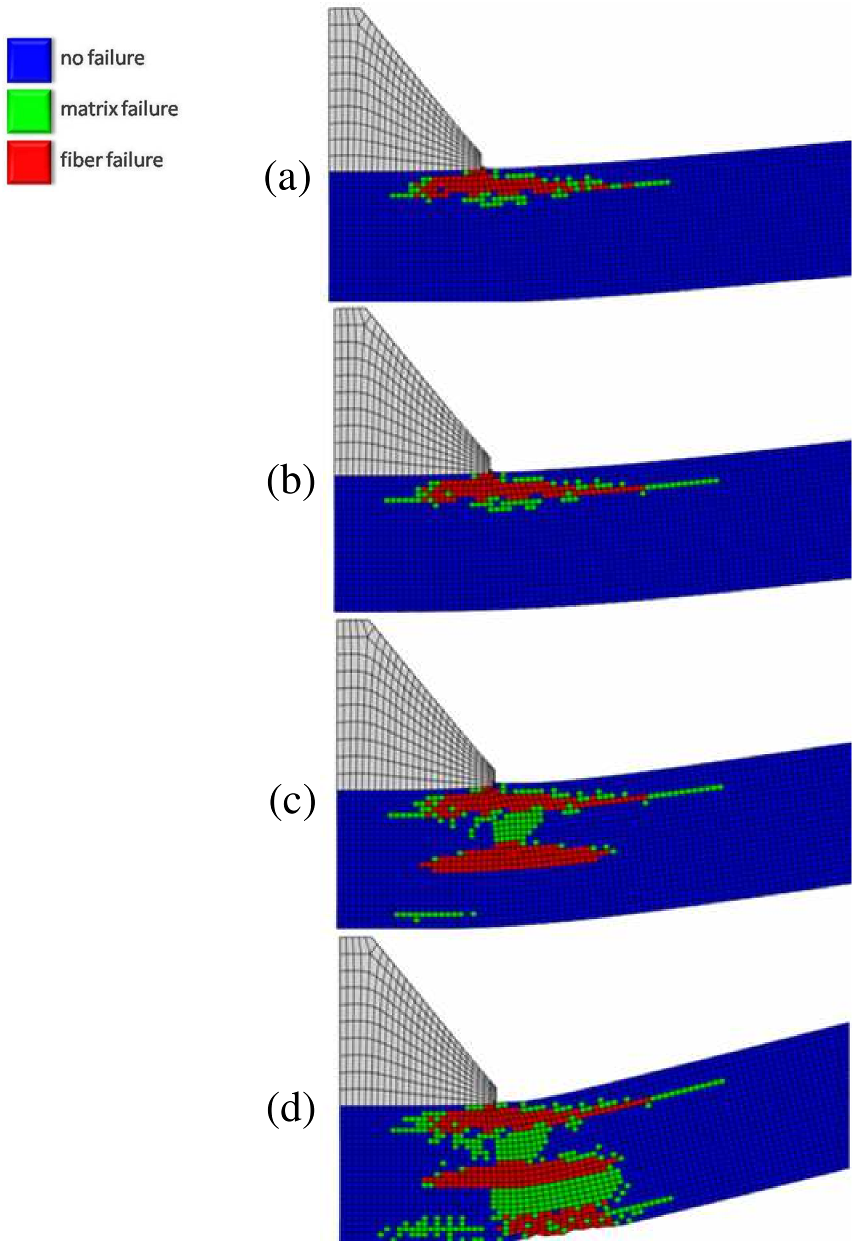

Figure 4. (a) Failure progression immediately after the first failure event, displacement = 8.6mm, (b) Failure progression prior to the second failure event, displacement=10.2 mm, (c) Failure progression after second damage event, displacement=10.4mm, (d) Failure progression after the third failure event, displacement=14.8 mm

Sensitivity of the Solution to Constituent Degradation Models

A comparison of continuous matrix degradation versus the instantaneous (discrete) matrix degradation of the baseline model is shown in Figure 5. The analyses are nearly identical through the second failure event. However, the continuous degradation model does not show a third distinct failure event.

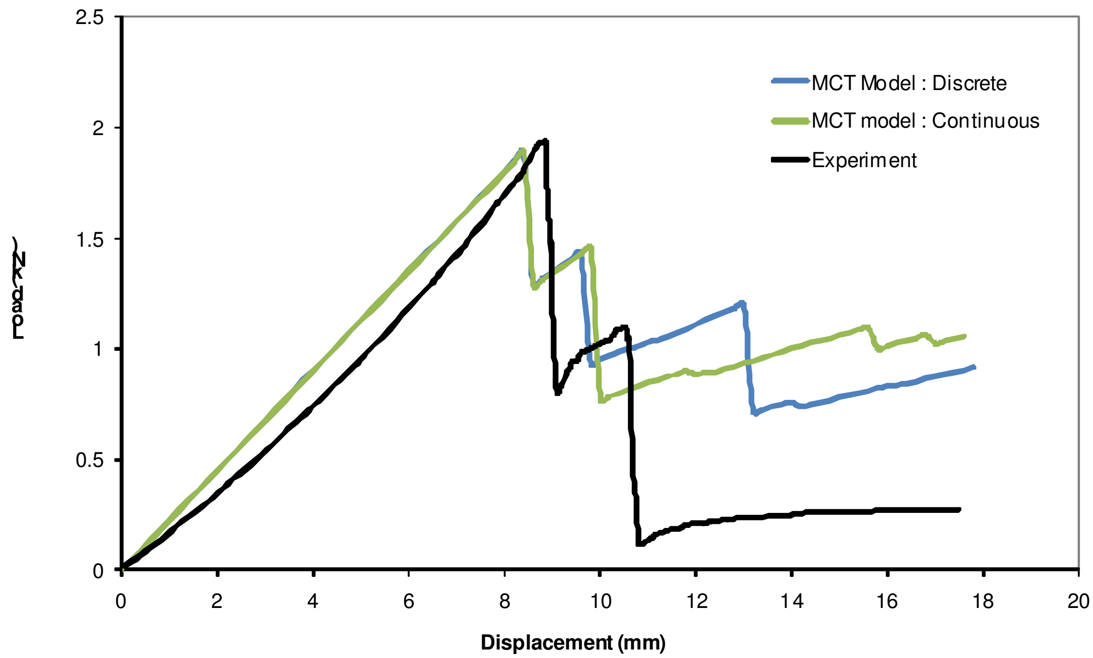

Figure 5. Comparison of load-displacement predictions for continuous and instantaneous matrix degradation models.

The computational speed of the discrete matrix degradation model and the modest post-failure differences in the two approaches suggests the discrete model is superior for the present problem. In what follows, we perform a sensitivity study on the values of constituent stiffness reduction for the discrete degradation approach.

Perhaps the most understudied aspect of the multicontinuum progressive failure algorithm is the fiber degradation value, E_f*. For many composites problems that are dominated by in-plane load, this value is not critical as any significant degradation value will quickly lead to ultimate failure of the lamina, realistically simulating the response. However for this bending problem, fiber failure in the first layer does not cause ultimate failure of the laminate, thus the degradation value, E_f*, may influence the solution.

Figure 6 shows the variation in the solution for values E_f*=1%, 0.1%, and 0.001%. As expected, the first failure event is predicted at exactly the same value for each of the three E_f* values. The most pronounced effect of altering E_f* can be seen in the magnitude of load drop after the first failure event and the predicted peak load for the second failure event. An E_f* value of 0.001% produces the best agreement of the post-failure load drops seen in the first and second failure events. The trend in the three analyses suggests even lower degradation values of the fiber modulus may produce extremely close agreement with the experimental post-failure response.

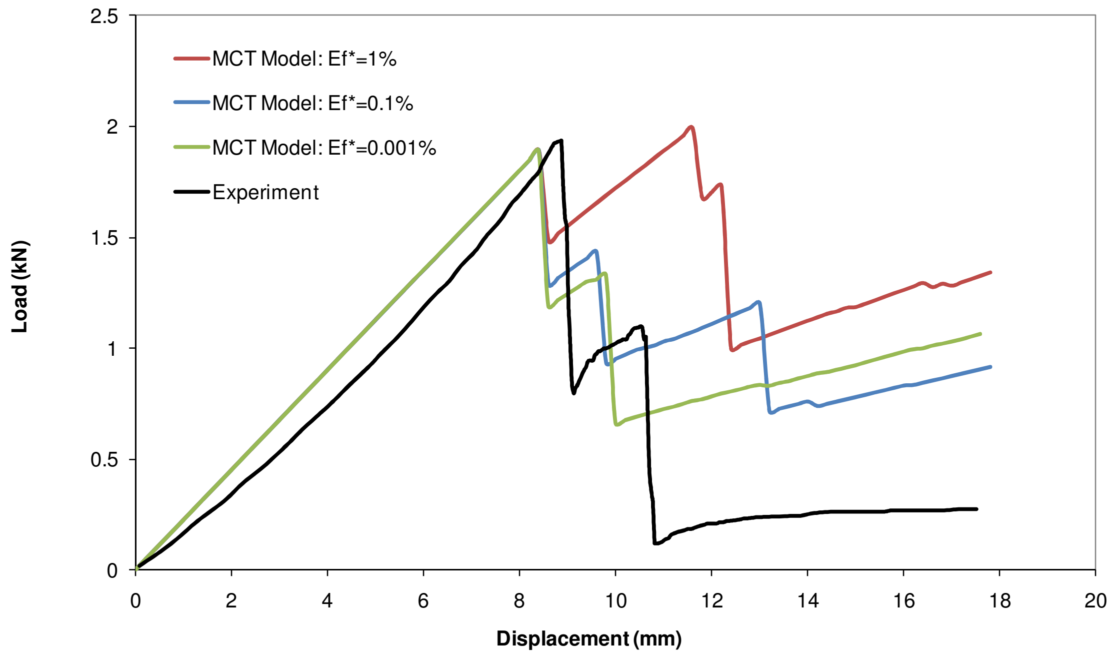

Figure 6. Load displacement comparison of the sensitivity of the MCT model predctions to variation of the parameter E_f*.

In considering matrix degradation, Tsai [11] reports the amount of matrix degradation upon crack saturation is a material dependent parameter that typically ranges from 4% to 15% of the original stiffness. Figure 7 shows the sensitivity of the solution to matrix degradation values of E_m* equal to 5, 10, and 15%, respectively. As expected, the first failure event is predicted at the same value regardless of the value of E_m*. Like the fiber degradation study, differing values of matrix degradation produce intuitively appealing trends in predicting intermediate failure events. Moreover, notice that the final modulus for each of these variations converges to a slope very representative of the experimental response.

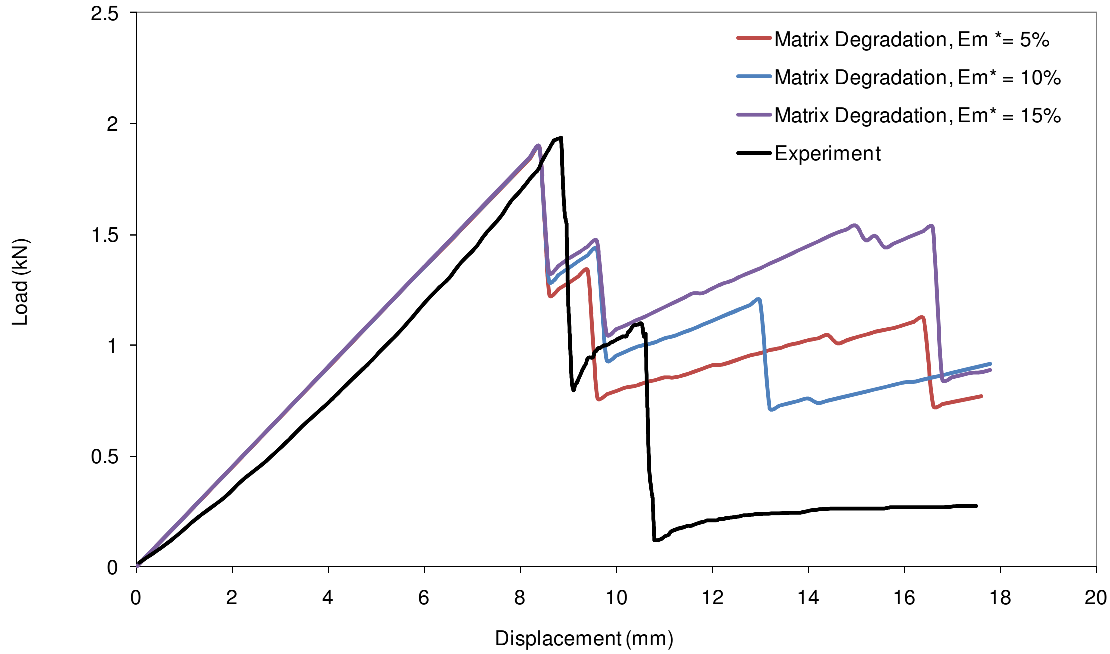

Figure 7. Load displacement comparison of the sensitivity of the MCT model predctions to variation of the parameter E_m*.

A Structural Analyst's Prospective: Solution Variation with Element Changes

A challenge encountered by all practicing structural analysts is model development. Many element types exist commercially that are applicable for modeling of composite structures. Three-dimensional solid elements, used in all of the analyses presented above, are workhorse elements; representing the response of structures as accurately as the finite element method allows. However, in large structures, representing each composite ply with multiple elements through its thickness is often untenable. Layered solid elements provide the ability to capture multiple composite plies within a solid element and still capture all components of the stress tensor. Solid-shell or continuum shell elements have recently gained traction, as they provide layered element capabilities but neglect any out-of-plane stress components.

This section provides details of a study of the change in solution results with varying element type to quantify the change of solution accuracy. One comparison model uses a single reduced integration layered-solid element with multiple integration points through the thickness to represent each material ply. A second comparison model uses a single continuum shell element to represent each material layer.

Figure 8 shows predicted load displacement curves provided by the various element types. Neither the composite solid nor the continuum shell models predict the first failure event with that same accuracy as the baseline model as failure values are 18-20% too high. We attribute the loss of accuracy to reduced kinematic freedom imposed by the layered elements. The composite solid layered element model appears to provide better performance in predicting the post-failure response than the layered continuum shell, perhaps indicating the through-thickness stress is important.

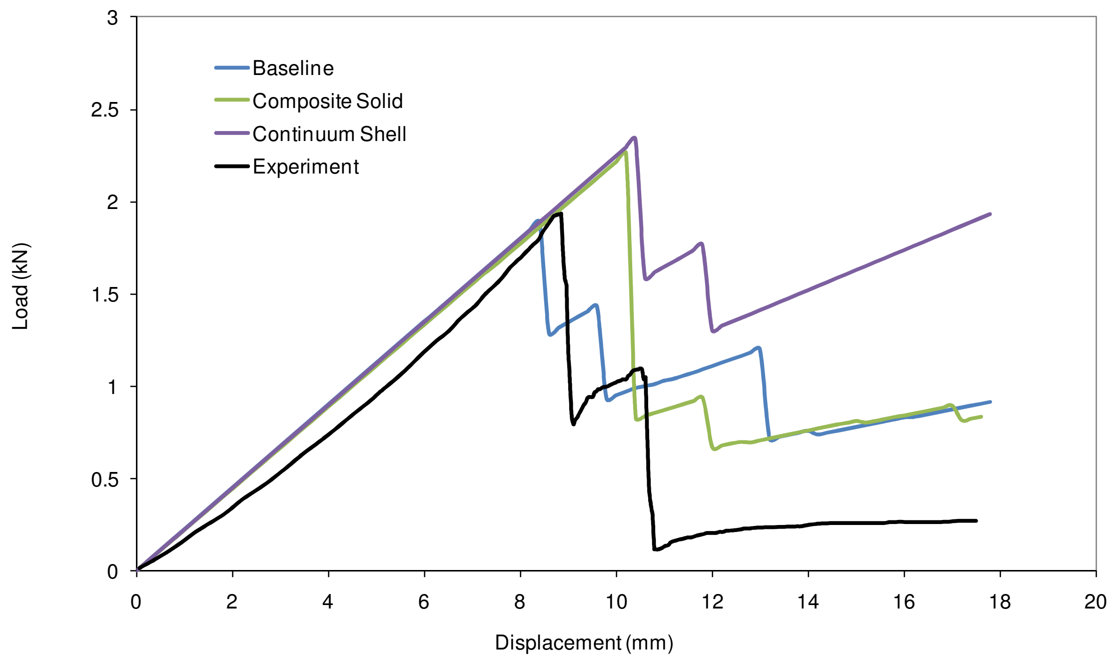

Figure 8. Analysis predictions using layered solid and layered shell elements compared against the baseline model and experimental data.

Although accuracy is lost using both the composite solid and continuum shell elements, both provide reasonable approximations for the failure response of the beam and require significantly less CPU run time. The composite solid model required 118 seconds of CPU run time while the continuum shell model required 62 seconds of CPU time. In contrast, the baseline model required 1700 seconds to complete a nonlinear analysis. Hence, a 20% loss in accuracy was counteracted by a 93% reduction in run time. Regardless of element choice, the multicontinuum progressive failure analysis provides a reasonable initial failure and post-failure response prediction.

Discussion

The goal of the multicontinuum approach is to provide a computationally efficient analysis that captures constituent level damage effects while delivering meaningful structural level performance information for the analyst. It is important to distinguish MCT constituent information from microstructural stress/strain fields found in many combined micro/macro structural analyses. The use of micromechanics point stresses in any failure analysis is questionable as they are inherently strongly dependent on fiber packing arrangements. Moreover, the computational demands associated with nonlinear micro/macro approaches combined with simple information overload makes make such analyses unfeasible for any structure of even mild complexity.

The multicontinuum failure theory uses a three-dimensional stress interactive failure criterion in the matrix constituent that has performed extremely well in a wide variety of in-plane, multi-axial loading situations. In this article, for the first time, the theory was compared to a loading scenario dominated by out-of-plane loads and delamination failure. Results of the analysis are in excellent correlation with the experimental data and suggest that the MCT approach is capable of simulating delamination as a failure mode. The significance of this result should not be understated as it may reduce the need for separate failure criteria for in-plane and out-of-plane failure modes.

Analytical predictions of the first failure event of three-point bend tests are excellent and the post-failure response was captured qualitatively but the magnitude of the initial load drop-off was not accurately predicted. We believe an advanced material model or coupling the approach with a cohesive element approach may warrant further investigation because the simple material property degradation model use is unable to capture the opening behavior caused by the delamination.

Material degradation approaches were investigated to determine their influence on the solution. Each approach studied affected the post-failure damage progression but the major events remained consistent indicating a robust and stable analysis. Perhaps the most useful follow-on work would be further studies of fiber degradation models.

Finally, a study on the effect of element selection was also performed to highlight the tradeoff between accuracy and efficiency. Advanced layered elements reduced the accuracy of the solution but provide reasonable estimates of the response with an order of magnitude reduction in solution times.

Acknowledgement

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