

SIMULATING DAMAGE TOLERANCE IN COMPOSITE STRUCTURES

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ABSTRACT

Damage tolerance is the attribute of a structure that permits it to retain a required structural strength or stiffness after it has sustained accidental or discrete damage. Current aircraft industry practice for assessing the damage tolerance of composite structures includes consulting source documents which are compiled from expensive and time consuming experimental programs. The result of this assessment is at best bounding estimates of the residual strength and stiffness of the structure.

Finite element based, multi-scale, progressive failure analysis is used to predict the residual strength and stiffness of impacted plates loaded in compression (compression after impact) and notched plates loaded in compression (open-hole compression). Comparisons of simulation results to experimental results show good agreement. A demonstration of scalability to large structures is also shown. Results indicate that using simulation to assess a structure's damage tolerance is feasible and would reduce the time and expense required to create source documents and enable engineers to make cost effective decisions on how to appropriately manage damage in composite structures.

1. INTRODUCTION

Damage in composite materials can be caused by a number of failure events and the extent and type of damage varies from small surface scratches to delamination and fiber fracture. Assessing the ability of an aircraft structure to survive and function in the presence of damage is critical to the design, certification, and overall safety of the aircraft. Using current industry methods, much of the damage tolerance assessment is determined by experimental testing of worst case conditions, i.e. testing structural components with holes sized to the worst expected damage. Although effective, this is extremely costly and time consuming. Also, a limited number of scenarios can be explored using this method. The ability to accurately simulate the effects of damage would be extremely valuable not only in reducing the costs and time required for experimental testing, but would allow numerous additional damage scenarios to be investigated. This study uses finite element based, multi-scale, non-linear progressive failure analysis to assess the residual strength and stiffness of a damaged component.

1.1 Progressive Failure, Multi-Scale Approach

When a composite structure has sustained a damage event or when a manufacturing flaw is discovered in the structure, it is necessary to determine if the structure can sustain continued use, if it needs a repair, or if it is not longer usable. This is not a trivial task since there are many

types of damage events and resulting failure modes. Example of damage types and failure modes are barely-visible scratches and gouges, delamination, environmental degradation, fiber-matrix splitting, buckling, and impact. Further, after the failure event, characterizing the extent and degree of failure using non-destructive methods can be expensive or simply not possible.

Multiscale analysis refers to treating analysis at multiple scales, in the case of a composite, this means at the micro-scale and the lamina scale. The Multicontinuum Theory (MCT) is a version of multiscale analysis. It applies continuum mechanics, the representation by average values of quantity, across multiple materials (two in this case) whose physical dimensions are small in comparison to the physical dimensions of the system of interest, yet large enough to capture average behavior. First described by Hill [1], the method evolved from Garnich and Hansen’s original proposal [2] to Mayes and Hansen’s [3], [4] failure analysis addition and then Nelson, Hansen and Mayes [5] provided improved solutions.

Building on traditional continuum mechanics to determine stress and strain fields for a composite at a point of interest, micromechanics are utilized to establish the needed relationship between the composite and constituents (fiber and matrix). Average constituent stresses and strains are decomposed from the composite results. A schematic of the multicontinuum hypothesis is shown in Figure 1.

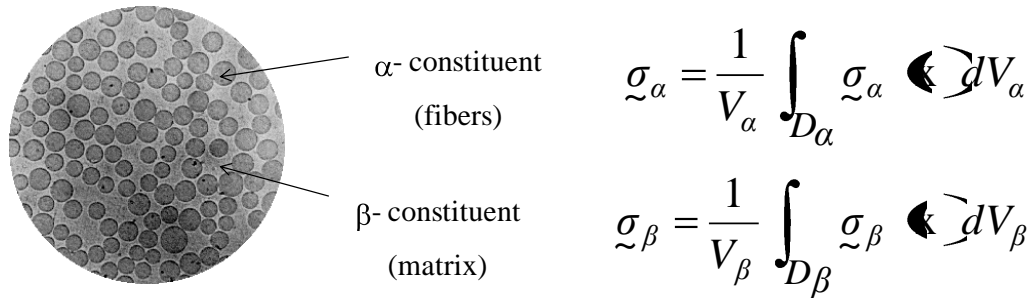


Figure 1. The Multicontinuum Concept.

Traditional composite analysis methods apply continuum mechanics to a single homogeneous medium. Often dubbed the black aluminum approach, interactions between constituents are neglected. As the presence of two unique materials in a composite distinguish structural response, the MCT approach addresses the constituents and interactions thereof. Having the ability to apply separate and distinct failure theories to the fiber and the matrix allows the MCT approach to address the unique behavior of each constituent. Readily coupled for the finite element method, MCT has been commercialized as the software product Helius:MCT™, an add-on for several finite element analysis software packages.

Progressive failure analysis is a nonlinear analysis technique where element integration point stiffnesses are reduced when a failure event is realized. In the case of an MCT progressive failure analysis, the fiber and matrix are treated separately and different stiffness degradation schemes are used for each. A unique feature of the MCT approach is that initial conditions can be used to assign a “damaged state” to the fiber constituent, matrix constituent or both

constituents in a region prior to beginning an analysis. This allows the analyst to use simulation to assess the effect of damage on the residual strength and stiffness of the structure.

1.2 Experimental Benchmark

To validate a numerical methodology for analyzing damage tolerance, it is necessary to benchmark the method against documented experimental results. In this work, a finite element study was conducted that was based on a compression after impact (CAI) experiment performed by Lee and Soutis [6]. In their experimental investigation, a circular, flat-nosed impactor mass was dropped from a specific height onto the center of a carbon-epoxy plate. The damaged plate was then loaded in compression until ultimate failure. The energy of the impact was determined from the mass and velocity of the impactor and the extent of damage in the plate was determined using ultrasonic C-scans and X-ray radiography. By measuring the size of the darkest regions in the X-ray images, they determined the damaged zone was 18 mm in diameter for an incident energy of 18.7 J. They also tested an open-hole plate in compression (OHC) where the diameter of the hole matched the diameter of the damaged region from the CAI plate. The OHC model was included so that a comparison could be made between the strengths of the CAI plate and a plate with zero stiffness in the damaged region.

In what follows, a description of the damage tolerance simulation, presentation of results, and comparison of simulation to experiment are given. In addition, scalability of the numerical method to large structures is demonstrated.

2. SIMULATION

2.1 Material

The material studied was unidirectional IM7/8552 which is manufactured by Hexcel Corporation. All materials stiffnesses and strengths except for interlaminar properties were provided in the experimental report [6] and are given in Table 1. The interlaminar properties, specifically G_{23} , ν_{23} , and S_{23} were estimated based on engineering judgment and typical values for intermediate modulus carbon/epoxy systems. The multi-scale material model utilized by MCT requires stiffnesses of the fiber, matrix, and lamina in addition to a fiber volume fraction to converge on a material model. As a result, the material stiffnesses in Table 1 differ slightly from the values reported by Lee and Soutis.

Table 1. Material properties of IM7/8552.

Property	Unit	Value	Property	Unit	Value
E11	GPa	150	S11	MPa	2400
E22 = E33	GPa	11	-S11	MPa	1300
G12 = G13	GPa	4.6	S22 = S33	MPa	50
G23	GPa	3.6	-S22 = -S33	MPa	250
$\nu_{12} = \nu_{13}$	-	0.30	S12 = S13	MPa	85
ν_{23}	-	0.36	S23	MPa	56

2.2 Geometry and Mesh

The dimensions of the model are identical to the dimensions of the experimental OHC specimens. The width of the plate is 100 mm, the length is 110 mm, the thickness is 3 mm, and the layup is $[45/-45/0/90]_{3S}$.

The meshes for the CAI and OHC models are shown in Figure 2. Aside from the hole in the OHC model, both meshes are identical. Abaqus element type C3D8R, which are 8-node, reduced integration, three-dimensional elements were used. Each material ply is modeled using a single element through the thickness, resulting in a total of 68,544 elements for the CAI model and 66,720 elements for the OHC model. This approach, while computationally more expensive than layered elements, is desirable for modeling damage tolerance because it allows the user to specify the depth of damage in addition to the planar area. Another advantage of using discrete layers is that the consequences of failure are more apparent since the entire element undergoes a stiffness reduction when failure is detected in the element. In layered elements, on the other hand, when an individual layer (single integration point) undergoes a failure event, the overall stiffness of the element remains essentially the same. Obviously, failure of an individual element will have a greater effect as the number of plies in the element decrease, but in this case, the layup is 24 plies.

The red highlighted elements in Figure 2(a) are the elements that use damage tolerance to simulate the impact damage. In this study, three models were analyzed. In the first model, the matrix constituent in the damaged region had a stiffness equal to 10% of the undamaged stiffness and the fiber constituent was undamaged. In the second model, the matrix constituent stiffness was reduced to 10% and the fiber constituent was reduced to 1% of their respective undamaged stiffnesses. Finally, an open-hole model was analyzed.

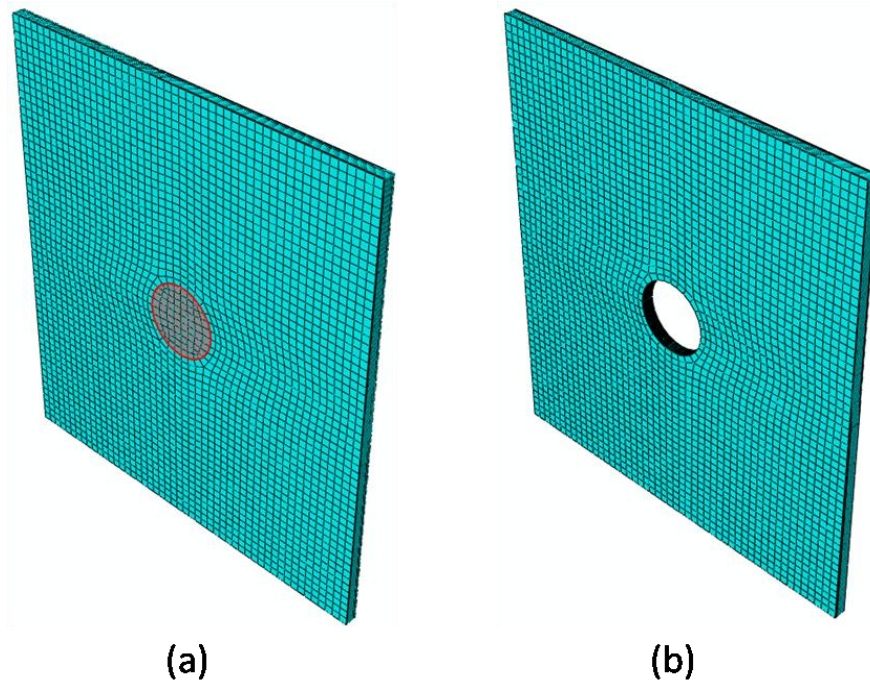


Figure 2. (a) CAI and (b) OHC meshes.

2.3 Model Boundary Conditions

The impact load was not simulated for the CAI model. Instead, initial conditions are used to reduce the stiffness of the impacted region prior to applying the compressive load. The compressive load is applied to the top surface of the plate and is displacement controlled. Constraints on the top surface maintain uniform displacement in the compressive direction; otherwise, the top surface is unconstrained. The bottom surface is pinned in the loaded direction and two mid-width nodes on the bottom surface are pinned to prevent lateral movement of the plate. In the experiment, the specimen is constrained against out of plane, macroscopic buckling using a fixture similar to what is specified in the ASTM standard ASTM D7136/D7136M-07. The fixture uses constraining sleeves that contact a small portion of the vertical edges of the specimen. In the model, the middle nodes on the sides of the plate are pinned in the out-of-plane direction to simulate the side-supports of the experimental test fixture which prevent buckling of the plate. This technique is chosen to eliminate the difficulties with simulating contact, and since failure does not initiate at the boundary, the chosen technique is deemed valid. The side and bottom boundary conditions are shown in Figure 3.

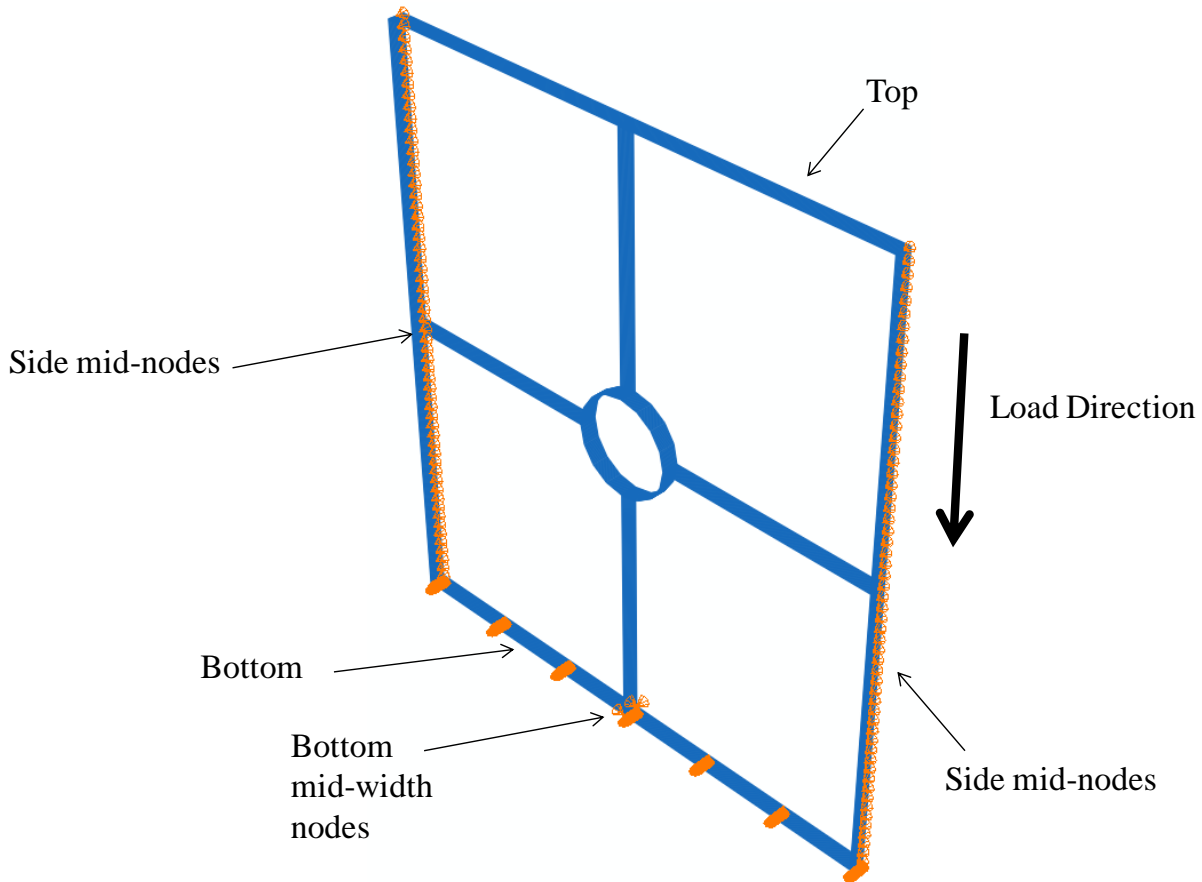


Figure 3. Boundary conditions on the side and bottom surfaces of the plate.

3. RESULTS

Load displacement plots for all three simulations are shown in Figure 4. Note that ultimate failure is defined here as a sudden decrease in the global stiffness, indicating a loss of load carrying capability. The model with matrix damage only (matrix DT) has a higher stiffness and a higher strength than the model with fiber and matrix damage (fiber DT) and the OHC model. The increase in stiffness in the matrix DT model can be attributed to the fibers in the damaged region having full stiffness. The strength difference can also be attributed to the intact fibers in the matrix DT model which allow load to be transferred through the damaged region as opposed to the OHC and fiber DT models where the load path is forced to go around the damaged region resulting in larger stress concentrations near the notch.

The fiber DT and OHC models have nearly identical stiffnesses and strengths signifying that the stiffness of the damaged region (1% for the fiber constituent and 10% for the matrix constituent) is too small to transfer significant load.

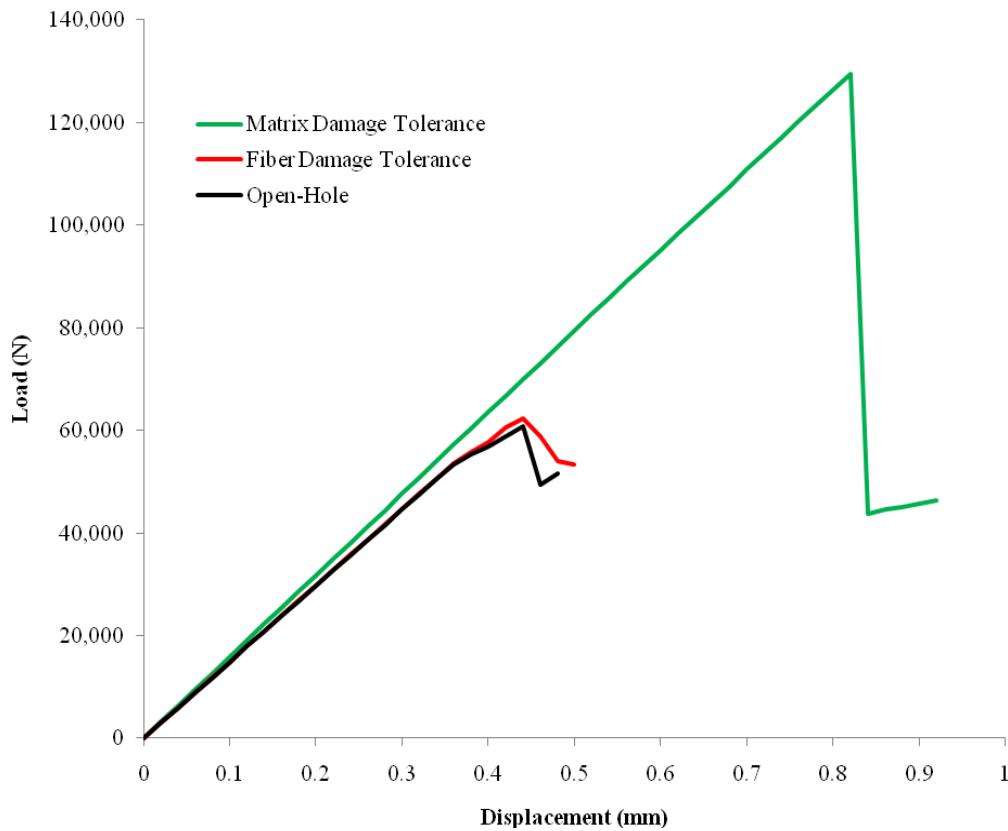


Figure 4. Load-displacement plots for matrix DT, fiber DT, and OHC models.

3.1 Strength Comparison

The experimental and model strengths are given in Table 2. The experimental CAI and OHC strengths are 242 and 229 MPa, respectively, indicating that the impact damage was so severe that the damaged region is effectively a hole. The fiber DT and OHC model strengths are 208

and 203 MPa, respectively, which is similar to the trend observed in the experiments where the damaged and OHC plates had similar strengths. This shows that the damaged region in the fiber DT model is also effectively a hole, which as mentioned earlier, is an intuitive result since the constituent stiffnesses in the damaged area are too small to transfer significant load.

The experimental strengths are in good agreement with the numerical strengths, with the exception of the matrix DT model. The numerical fiber DT and experimental CAI strengths differ by 14% and the OHC strengths differ by 16%. The matrix DT strength, however, is nearly double the experimental strengths since the damaged region in the matrix DT model still has significant load carrying capacity, which alleviates the stress concentration and allows the plate to sustain higher loading. During the experiment, the authors observed matrix cracking, delamination, and fiber splitting and fracture in the damaged region of the plates after impact and prior to compressive loading. Since the impact caused more than just matrix damage, this suggests that degrading the matrix constituent only is inadequate and does not capture the true extent of failure in the impacted plate and it explains why the fiber DT model strength is close to the experimental strength.

Table 2. Experimental and model strengths.

	Strength (MPa)
Experimental	
CAI	242
OHC	229
Numerical	
Matrix DT	431
Fiber DT	208
OHC	203

3.2 Failure Mode Comparison

When the impacted plate was being loaded, the authors observed, "...damage in the form of local buckling like a crack grows laterally from the impact damage region." Figure 5 shows the progression of damage through the displacement history in the 0° plies in the fiber DT model. Note that the numbers in the figure correspond to the compressive displacement. Damage initiates at the edges of the damaged region and propagates in a direction perpendicular to the loading direction as the load is increased, very similar to what was observed in the experiment. Note that in Figure 5, blue elements have no damage, green elements represent material with matrix damage, and red elements represent material with fiber and matrix damage. As previously stated, when matrix failure is detected, the stiffness of the matrix is reduced 90% and when fiber failure is detected, the stiffness of the matrix is reduced 90% and the stiffness of the fiber is reduced 99%.

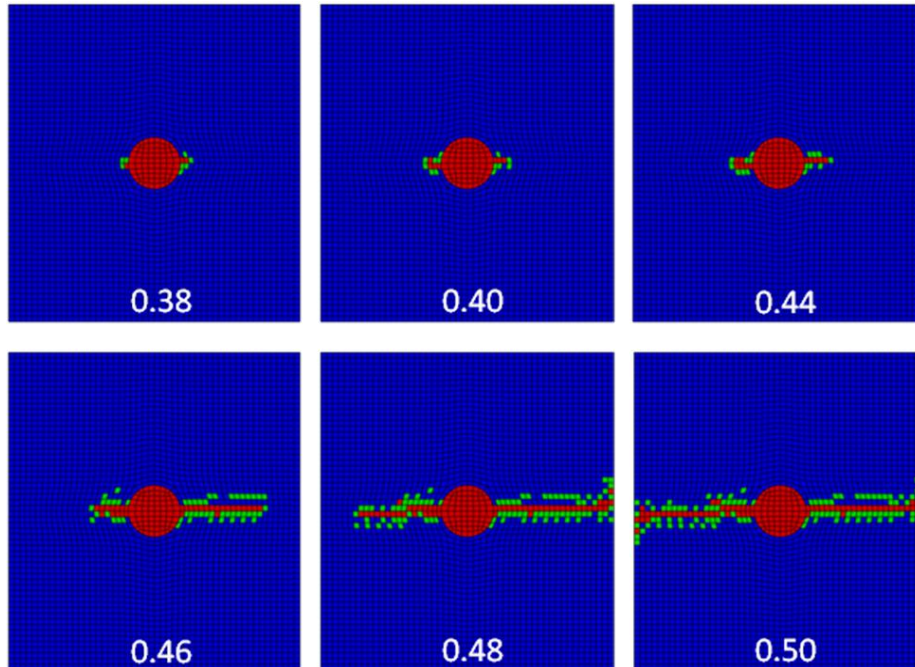


Figure 5. Failure progression of the 0° plies in the fiber DT model (blue = undamaged, green = matrix failure, red = matrix and fiber failure).

4. SCALABILITY

To demonstrate the scalability of using multi-scale, progressive failure analysis, consider the composite wing box shown in Figure 6. Suppose a damage event occurred on the leading edge of the wing that resulted in noticeable fiber and matrix damage. The damaged region, represented by the red elements, is assigned degraded material properties prior to the start of the analysis. The deflection profile of the wing at the design flight load is important because many wings have mechanical devices, such as flaps, that will not function properly if the wing deflection is too severe. The deflection profiles of the damaged and undamaged wings at the design load are shown in Figure 7. Near the wing root, the deflections are identical, but they diverge at the damaged region. This result was obtained with a simple change to the input file and would provide the analyst with additional information to help determine if the wing is still usable.

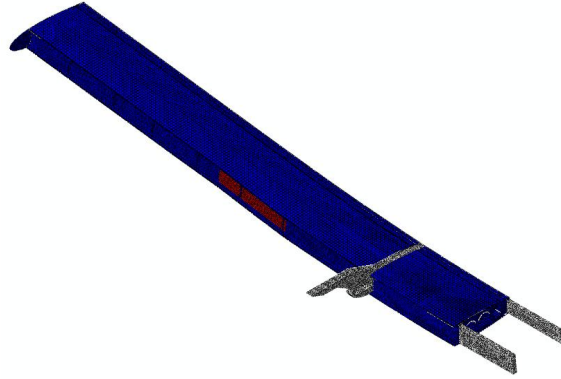


Figure 6. Wing box with damaged region highlighted in red.

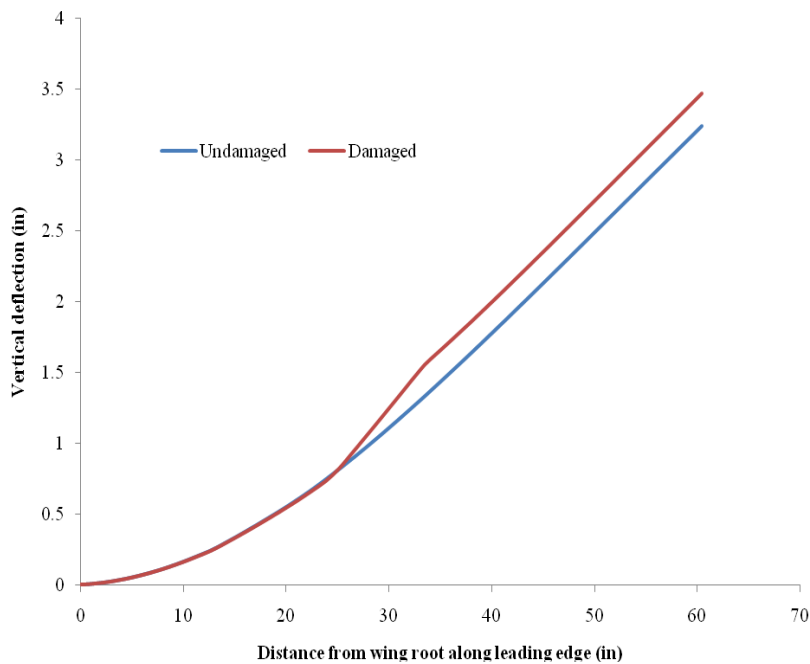


Figure 7. Wing box deflection profiles.

5. CONCLUSIONS

Three finite element models based on CAI and OHC experiments were developed using the damage tolerance functionality in Heliuss:MCT. The simulated CAI strength using fiber damage tolerance was in good agreement with the experimental CAI strength. The results suggest multi-scale material degradation is a promising method for understanding damage tolerance in structures.

Multi-scale material degradation in combination with modeling techniques is attractive because, in addition to control over which constituent to fail, it gives the user control over the consequences of failure (i.e. control over the amount of stiffness degradation to apply to the matrix and fiber constituents). For example, delamination could be simulated by heavily degrading the matrix properties in a thin layer of elements, fiber-matrix splitting could be

simulated by heavily degrading the matrix properties in a thin row of elements, and impacts can be modeling by moderately degrading the matrix and fiber constituents as shown in this study.

6. REFERENCES

1. Hill R. "Elastic Properties of Reinforced Solids: Some Theoretical Principles." *Journal of the Mechanics and Physics of Solids* 11 (1963): 357-372.
2. Garnich M. and Hansen A. "A Multicontinuum Approach to Structural Analysis of Linear Viscoelastic Composite Materials." *Journal of Applied Mechanics* 64 (1997): 795-803.
3. Mayes J. and Hansen A. "Composite Laminate Failure Analysis using Multicontinuum Theory." *Composites Science and Technology* 64 (2004): 379-394.
4. Mayes J. and Hansen A. "A Comparison of Multicontinuum Theory based Failure Simulation with Experimental Results." *Composites Science and Technology* 64 (2004): 517-527.
5. Nelson E., Hansen A. and Mayes J. "Failure Analysis of Composite Laminate Subjected to Hydrostatic Stresses: A Multicontinuum Approach." Accepted as part of the second world wide failure exercise.
6. Lee J. and Soutic C. "Experimental Investigation on the Behavior of CFRP Laminated Composites under Impact and Compression After Impact (CAI)." *Proceedings of the EU-Korea Conference on Science and Technology Book Series: Springer Proceedings in Physics* 124 (2008): 275-286.

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