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TECHNOLOGIES
ADVANCED COMPOSITES ANALYSIS

Progressive Failure Analysis of Composites Made Easy

Achieving confidence in simulation using multiscale analysis

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3/29/2010

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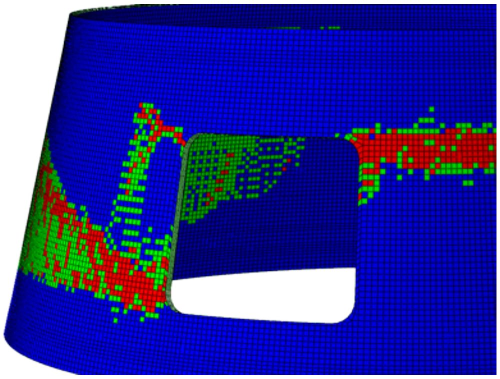

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INTRODUCTION

Failure of composite structures is a progressive series of events. Failure often starts as a tiny crack between the fibers and matrix. Continued loading leads to the formation of multiple cracks in the lamina. These cracks decrease the stiffness of the matrix causing the fibers or surrounding plies to carry a higher stress than they normally would. Capturing stress redistribution is the key to realistic simulation of composite structures failure.

Progressive failure is commonly underutilized in industry because of the difficulty in achieving a solution the analyst can have confidence in. This difficulty stems from convergence problems in general purpose finite element codes and inaccurate methods for predicting multiple failure modes. In turn, this had led industry to use very conservative first-ply-failure solutions, negating many of the optimization advantages that can be gained from composite materials. In the aerospace industry, such optimization can result in increased payload performance or reduced manufacturing and launch costs. This white paper will address these existing issues with composite progressive failure analysis and examine aspects of a new technology offering improved progressive failure solutions.

THE PROBLEM – COMPOSITE PROGRESSIVE FAILURE UNBELIEVABLE AND UNATTAINABLE

The advantages of understanding composite failure with accuracy are unattainable due to limitations of existing analysis methods.

One of the most valuable, but most challenging undertakings in composite design and analysis is modeling material and structural failure. Understanding how and when a structure will respond to loading conditions is crucial in verifying a structure will meet its requirements or determining how a design could be optimized.

This involves a desire to answer such questions as:

- ➢ Where does damage occur and how does it affect ultimate integrity of the structure?
- ➢ How and when does damage initiate?
- ➢ How much tolerance exists between initial, localized failure through ultimate failure?
- ➢ How do different load conditions affect the structural response?
- ➢ How do environmental factors affect the structural response?
- ➢ How can the design be optimized to improve performance and efficiency?

Unfortunately, the advantages of understanding composite failure with accuracy are usually unattainable due to the limitations of existing analysis methods.

Ground-breaking efforts in programs such as the World Wide Failure Exercise have demonstrated a general lack of accurate laminate failure predictions by the composites community [1]. It has been demonstrated that the various failure criterion widely accepted as industry-standard fail to provide accurate insight into the failure phenomena associated with composite structures.

PREVIOUS OPTIONS

There are several engineering tools available to designers and analysts. However, realistic composite simulations are limited due to the following two obstacles:

- Inaccurate prediction of composite failure due to inherent errors in applied failure criterion
- General purpose FEA methods fail to converge

Inaccurate Analysis - Bad In = Bad Out

Traditional failure criterions are based on simplified failure envelopes for the homogenized laminate.

Conventional analysis approaches utilize use lamina strengths and effectively treat the material as if it were homogeneous (aka the "Black Aluminum" approach). In addition, they assume linear elasticity through ultimate failure. In doing so, critical phenomena of composite failure are overlooked. The composites community has long known of the deficiencies of these approaches and often use various design allowables based on specific sub-structures – such as open-hole tension tests – to account for the lack of confidence in simulations.

Composites fail distinctly different from homogeneous, linear-elastic materials.

Due to the non-homogeneous, constituent nature of composite materials, they fail in manners quite different than linear elastic, homogeneous materials (metals). First, they do not break or fail in a single event. Rather, it is a progressive, nonlinear phenomena beginning with local damage and continuing through ultimate failure. Also, they will exhibit different failure modes depending on the loading condition. For example, failure due to axial tension will usually be driven by fiber fracture while transverse tension will be driven by matrix fracture. Axial compression will be driven by fiber buckling and transverse compression by matrix compressive failure. In each case, the resulting behavior may vary drastically. It is illogical then to assume then that a curve-fit based on homogenized properties would provide accurate insight into distinct failure events.

No Convergent Solution – The Elusive Final Answer

Another common and painful problem associated with composite progressive failure analysis is the inability to reach a convergent solution. After meticulous efforts and hours of computation, the analysis crashes early in the failure progression due to convergence errors. Changing stabilization control and time incrementation parameters often does not resolve the problem. After hours or perhaps days of working and waiting, the analyst either chooses the last converged solution – even though there may be no appreciable reduction in stiffness – or abandons the analysis. In each case, a conclusive, believable result remains elusive.

Uncertainty Leads to Excessive Conservatism

The inability to achieve an accurate, convergent solution results in over-conservatism.

The result in both cases is uncertainty. The inability to model progressive damage and ultimate failure has driven designers to be excessively conservative and use inefficient assumptions. Without accurate knowledge of composite behavior, it is impossible to predict response to real-world conditions. This in turn prohibits true optimization and the realization of the benefits of composite materials.

THE SOLUTION – HELIUS:MCT™, PROGRESSIVE FAILURE: ACHIEVABLE AND BELIEVABLE

The answer to these problems requires a solution that addresses the specific mechanical behavior of composites and is practical for industry use. That solution is Helius:MCT.

The solution involves an efficient approach to multiscale analysis.

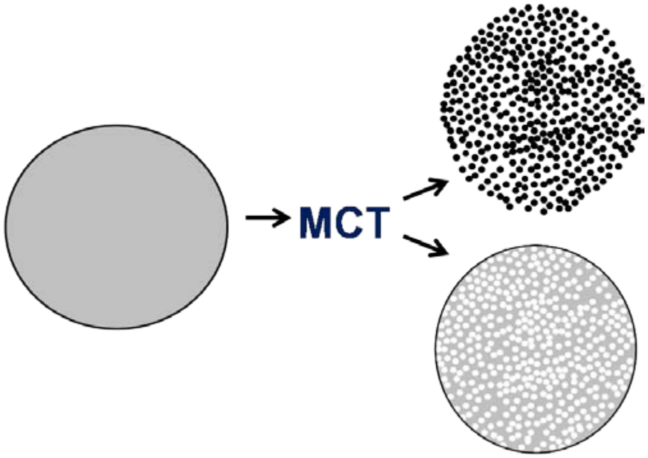
Many researchers have recognized the need for multiscale stress or strain information in order accurately capture the failure response of the constituents in a composite [2] [3] [4]. However, a fundamental challenge in doing so is to efficiently cross multiple scales to capture micro-structural information where failure initiates, while recognizing the practical constraints imposed by structural analysis. Helius:MCT offers a solution that delivers the accuracy of constituent-based failure analysis while incorporating a computational approach that is efficient and robust. The result is a convergent solution that is believable.

The keys to this solution are the combined applications of Multicontinuum Technology (MCT) and the Intelligent Discrete Softening (ISD) Method.

The Accuracy of Multicontinuum Technology

Multicontinuum Technology (MCT) decomposes the composite stress and strain into constituent stress and strain to predict distinct failure of the fiber and matrix.

Virtually all successful failure theories developed for composite laminates recognize that different failure criteria apply for the fiber and matrix within a composite material. Hashin [5] was one of the pioneers of such an approach when he proposed failure criteria for both the fiber and matrix materials within a composite based on the *composite* stress fields. In the spirit of Hashin, the multicontinuum theory employs independent failure modes of the fiber and matrix constituents. However, rather than utilize *composite* stresses to predict *constituent* failure, MCT utilizes *constituent* stresses to predict *constituent* failure of the fiber and matrix. Continuum level constituent information may be generated in a numerically efficient manner utilizing a multiscale decomposition originally developed by Hill [6].



Failure in composites laminates can be summarized by a progression of the following events which must be captured in order to achieve an accurate failure simulation:

- Local matrix failure
- Matrix failure propagation
- Local fiber failure
- Fiber failure propagation
- Ultimate failure

Helius:MCT addresses the constituent-based, nonlinear failure modes of composite materials.

Each causes a reduction in stiffness, which in turn causes stress to redistribute. The sequence of events varies based upon the loading scenario. Additionally, this progression of non-continuous, discrete events occurring separately in the matrix and fiber constituents often results in nonlinear behavior. Helius:MCT addresses both these phenomena by applying distinct failure criterion to the fiber and matrix and a stiffness degradation specialized for composite failure states[7,8].

Within a Helius:MCT simulation, ultimate failure in a structure is determined by tracking its global stiffness. When a large discontinuity is detected, global failure is predicted. These discontinuities are caused by the iteration of the following cycle: prediction of local failures, subsequent material degradation and stress redistribution there-by causing new local failures. Multiple iterations of this cycle create a cascade of local failures that coalesces into ultimate failure of the structure. This is a significant result because often global failure is determined by first ply failure or use of engineering judgment based on a contour plot. The presence of an ultimate failure criteria removes much guesswork from the analysts job.

Example – Progressive Failure Analysis of Large Space Structure

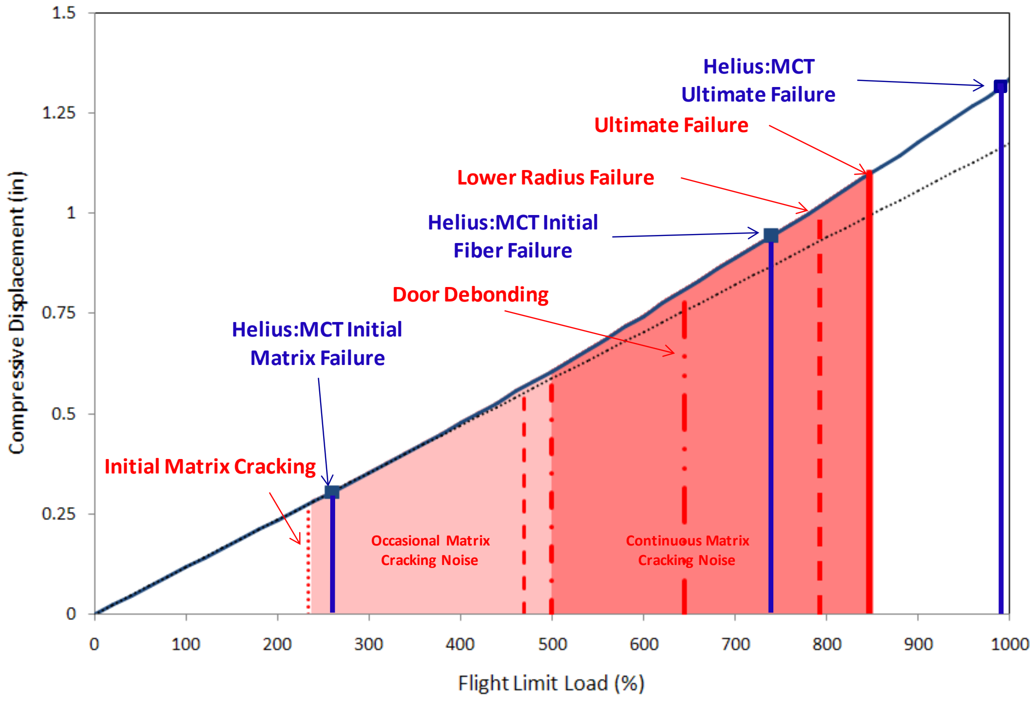
An excellent example of this is shown in the progressive failure analysis of a large composite space structure. This thick, all-composite structure is loaded primarily in bending. Failure of the structure is shown to be a series of events beginning with matrix cracking through fiber failure and ultimate failure. Failure of the structure initiates early on in the loading at 260% Flight Limit Load (FLL), but does not collapse until 850% FLL! It can be seen here that the results of analysis with Helius MCT (blue columns) correspond favourably with the physical test results (red columns).

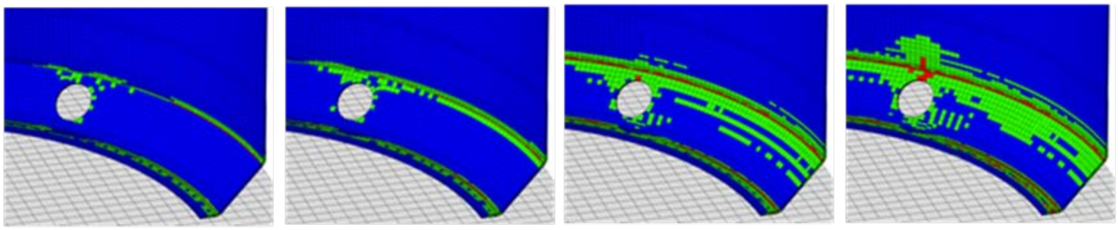
The Composite Adapter for Shared Payloads (CASPAR) and its simulation with Helius:MCT in Abaqus.

% FLL	Failure Event	%FLL	Helius:MCT Analytical Failure Event	% Difference
234	Initial matrix cracking sounds	**260**	**Initial matrix failure**	11
319-469	Occasional matrix cracking noise	261-480	Matrix failure progression	
470 +	Continuous matrix cracking noise	500 +	Rapid matrix failure progression	6.3
658	Fiber failure noise	740	First fiber failure	
792	Lower radius failure	800	Fiber failure in lower radius	1.0
847	Ultimate failure	980	Ultimate Failure	15.7

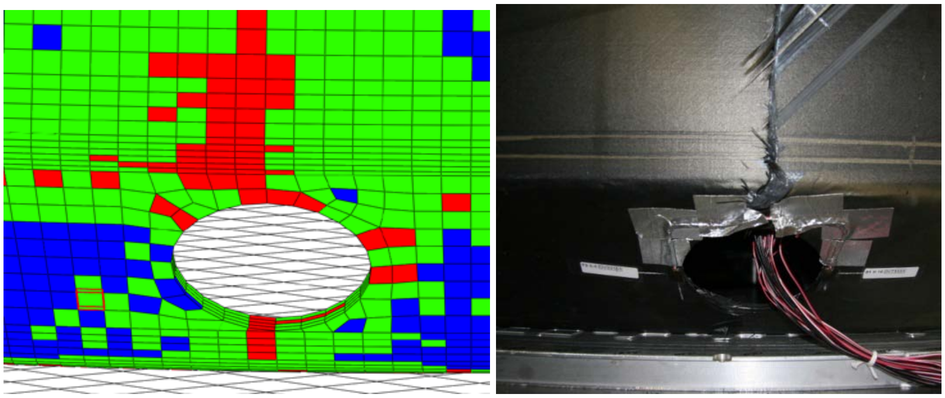
It is also shown that failure of the structure was a distinctly nonlinear event. The load displacement curve shows the distinct and slow progression by the gradual global stiffness reduction (nonlinear load displacement curve). Again, Helius:MCT analytical results are shown in blue and results of physical testing of the structure are shown in red. Note the global softening of the structure when compared to a linear elastic response (dotted line).

Analysis vs. structural test results demonstrate Helius:MCT closely predicts discrete failure events and non-linear behavior.





Helius:MCT results showing progressive failure of the lower, tapered radius of the CASPAR structure - Undamaged (blue) / Failed Matrix (green) / Failed Fibers (red)

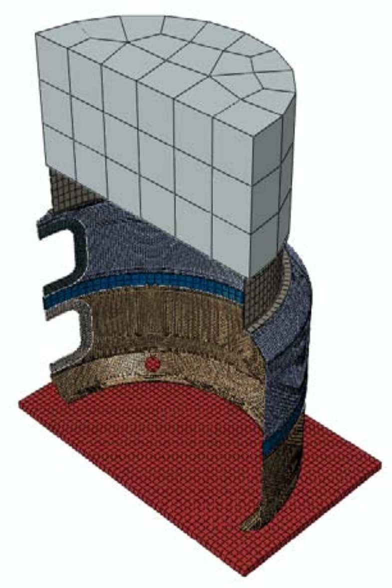


Close up of failed region at vent holes. Fiber failure in lower radius predicted through simulation to within 1% of tested load.

The Efficiency of the Intelligent Discrete Softening method

A softening method designed specifically for composites enables robust convergence.

The extreme convergence difficulty associated with progressive failure analysis of composites stems directly from this non-continuous (or discrete) softening behavior that composite materials exhibit as individual failure events accumulate within the composite microstructure. General purpose finite element codes are developed to handle a variety of material models, primarily continuous stiffening and softening schemes. Progressive failure of composite structures is a softening phenomenon; however, as it was shown above, it is generally not continuous as a small increase in load can create failure events in multiple elements in a single increment. General purpose finite element codes simply cannot provide robust solutions for structures that exhibit this type of material response. To overcome the difficulty that general purpose finite element codes have in obtaining converged solutions for progressive failure problems, Firehole Technologies has developed the Intelligent Discrete Softening Method (or IDS Method), which has been incorporated in Helius:MCT. By using the IDS Method, Helius:MCT ensures a robust convergence in all loading scenarios.

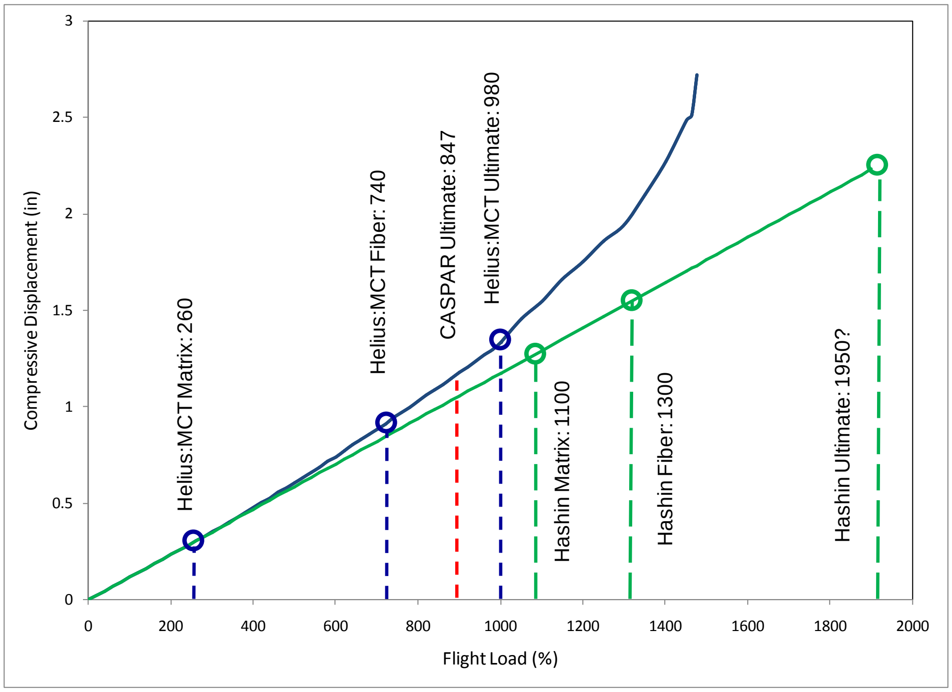


In the case of the space structure above, a detailed model was created using 3-D layered solid elements. Using Helius:MCT, the 122,000 element progressive failure simulation was completed in just 1.5 days on a desktop computer.

How does this compare to other methods?

Traditional methods could mask the non-linear degradation and overestimate structural strength significantly.

For comparison, let us look at how the MCT analysis stacks up to the current state-of-the art composite failure method available through existing commercial FEA packages. As mentioned earlier, the Hashin method is distinguished from other traditional failure criterion in that it differentiates between fiber and matrix failure. However, it still does not decompose the stress and strain of the composite into distinct constituent states. In this comparison, it is shown that the method's inability to capture the non-linear failure progression resulted in overestimation of matrix and fiber failures by 4x and 2x respectively. A linear response was predicted until 1960%FLL where the analysis then failed to converge.



In summary, it is shown that in a structural analysis, neglecting the diverse effects of composite constituents or treating the analysis as linear elastic, analytical solutions are at least more than two times greater than the experimental failure.

IMPLEMENTATION – PROGRESSIVE FAILURE REAL… AND EASY!

Helius:MCT was developed with the intent of expanding use of composites by enabling designers and engineers with an accurate, yet practical analysis tool. To that end, it incorporates these key elements of implementation:

✓ **Failure simulation technologies must integrate with commercial FEA packages**

Helius:MCT is delivered as an add-on to commercial finite element codes. Executed via a Graphical User Interface (GUI) within the host environment, it integrates seamlessly into commercial finite element codes. (Typically a layered element is used to resolve laminate stresses into lamina stresses. From there, the Helius:MCT code is called at each material point to supply constitutive information to the solver.)

Helius:MCT integrates seamlessly within your existing FEA package.

✓ Material characterization must use only standard input parameters

Material characterization and qualification is an expensive and time consuming process. It also is a critical, yet often over looked contributor to reliable failure simulation because the result is only as accurate as the input parameters.

Historically, open-hole or notched laminate specimens have been used to develop design criteria. These tests are costly, not generic, and cannot be applied to multiple lamination schemes. This expense has discouraged the use of new materials and optimizing lamination schemes, thus reducing many of the advantages of composites. Variations in manufacturing lead to application of "knock down factors", which further reduce confidence in simulations and increase conservatism.

Conversely, many recently developed failure theories require the use of exotic material parameters [2] [9], that can only be derived from expensive and time consuming testing methods that have not been widely accepted by the testing community or vetted as a standard test method.

Helius:MCT requires only standard material inputs.

Standard material inputs for a transversely isotropic composite are the elastic constants E_{11}, E_{22}, ν_{12}, ν_{23}, G_{12}, and the tensile and compressive strengths S_{11}, S_{22} and the shear strengths S_{12} and S_{23}. These can readily be determined from relatively inexpensive coupon testing or in many cases handbook [10] values of unidirectional lamina and are transferable between multiple applications. *The MCT approach has been specifically designed to require only these standard material inputs.*

✓ Computational efficiency is paramount

Using a robust, convergence algorithm, a solution is achieved in a minimal amount of time.

Excessive run times measured in weeks do not fit with development schedules and do not allow multiple analyses to be performed. Computational efficiency is inherent in the MCT method, in that only a small number of equations is added to the computation requirements for a single integration point. Application of the IDS Method also reduces overall time required to reach a convergent solution. These design elements combine to produce a believable result in a practical amount of time. The MCT algorithm increases the run time for a typical structural analysis by only 2 to 3%.

Summary – The Headaches of Composite Progressive Failure Analysis are Gone

The days of adjusting for inaccurate answers or coping with the inability to reach a solution are over. Modern technology has delivered a solution that can put advanced composite analysis technology feasibly into the hands of structural designers and analysts.

Helius:MCT has been implemented so that the headaches and time loss are eliminated from progressive failure analysis of composites. We make progressive failure doable, believable … and easy.

To learn more about the Helius:MCT progressive failure solution, visit us at www.fireholetech.com or call us at 1-307-460-4763

About Firehole Technologies

Firehole Technologies supplies innovative computer-aided simulation software and consulting services specializing in analysis of composite materials. Headquartered in Laramie, Wyoming, the company had its beginning in the academic research of composite analysis during the mid 1990's. The core technology behind MCT was developed through research conducted at the University of Wyoming. Founded in 2000, the company's mission is to enable wide-spread use of composite materials leading to lighter, stronger and more fuel efficient applications. For more information, visit www.fireholetech.com.

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