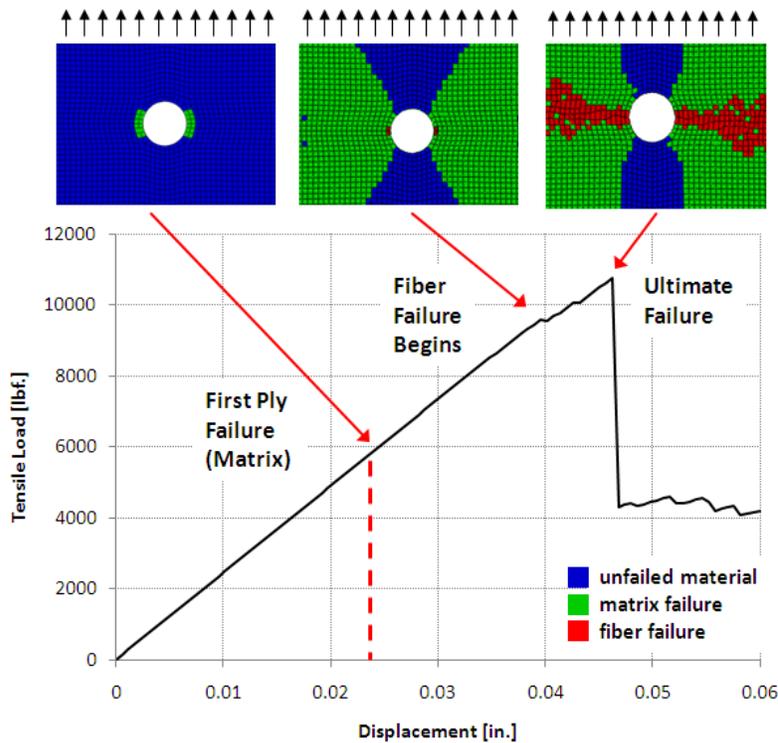


Overcoming Challenges in Progressive Failure Analysis of Composite Materials



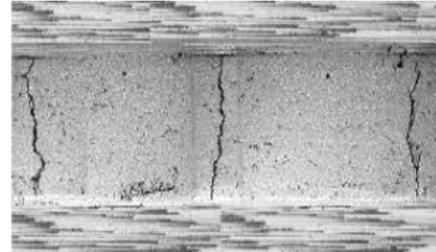
Composite material failure is a progression of discrete failure events occurring separately in the matrix and fiber constituents, usually resulting in nonlinear material behavior. Homogeneous, linear-elastic methods employed by most traditional failure criterion mask this unique phenomenon, resulting not only in inaccurate results, but often failing to converge on any solution at all. These significant challenges often prevent analysts from achieving a progressive failure analysis - confining them to conservative first-ply-failure solutions. The following paper will address the issues with composite progressive failure analysis and discuss how Autodesk® Heliu PFA has been developed to address these challenges.

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Introduction

Failure of composite structures is a progressive series of events. It often starts as a tiny crack between the fibers and matrix. Multiple cracks form in the lamina due to continued loading. These cracks decrease the stiffness of the matrix causing the fibers or surrounding plies to carry a higher stress than they normally would. Capturing this stress redistribution is the key to realistic simulation of failure in composite structures. But it is this phenomenon that causes significant challenges in achieving simulation of this *progressive failure*.



Progressive failure analysis is commonly underutilized in industry because of these and other challenges. Difficulties with general-purpose finite element codes include convergence issues and inaccurate methods for predicting the multiple failure modes found in composite materials. As a result, analysts often have difficulty in achieving a solution they can have confidence in. In turn, this has led industry to use very conservative first-ply-failure solutions, negating many of the optimization advantages that can be gained from composite materials. This white paper will address the existing issues with composite progressive failure analysis and examine aspects of Autodesk® Heliuss PFA that offer practical solutions to these challenges.

The Problem

Composite Progressive Failure is Unbelievable and Unattainable

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:

- How and when does damage initiate?
- Where does damage occur and how does it affect the ultimate integrity of the structure?
- How much tolerance exists between initial, localized failure and ultimate structural 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 answers to these questions are usually unattainable due to the limitations of existing analysis methods. Programs such as the World Wide Failure Exercise have demonstrated a general lack of accurate laminate failure predictive capability in the composites community^[1]. It has been shown 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 a multitude of 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 on a solution

Inaccurate Analysis: Bad In = Bad Out

Conventional analysis approaches 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 uses various design allowables based on specific sub-structures – such as open-hole tension tests – to account for the lack of confidence in simulations.

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, failure 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 that a curve-fit based on homogenized properties would provide accurate insight into such 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 altogether. In either case, a conclusive, believable result remains elusive.

Uncertainty Leads to Excessive Conservatism

The result in both cases is uncertainty. As a result, 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

Autodesk Heliuss PFA

The answer to these problems requires a solution that addresses the specific physical behavior of composites and is practical for industry use. That solution is Autodesk Heliuss PFA. 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. Autodesk Heliuss PFA 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 the Multicontinuum Technology

Virtually all successful failure theories developed for composite laminates recognize that different failure criteria apply for the fiber and matrix within a composite material. Hashin⁵ 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 Hill⁶.

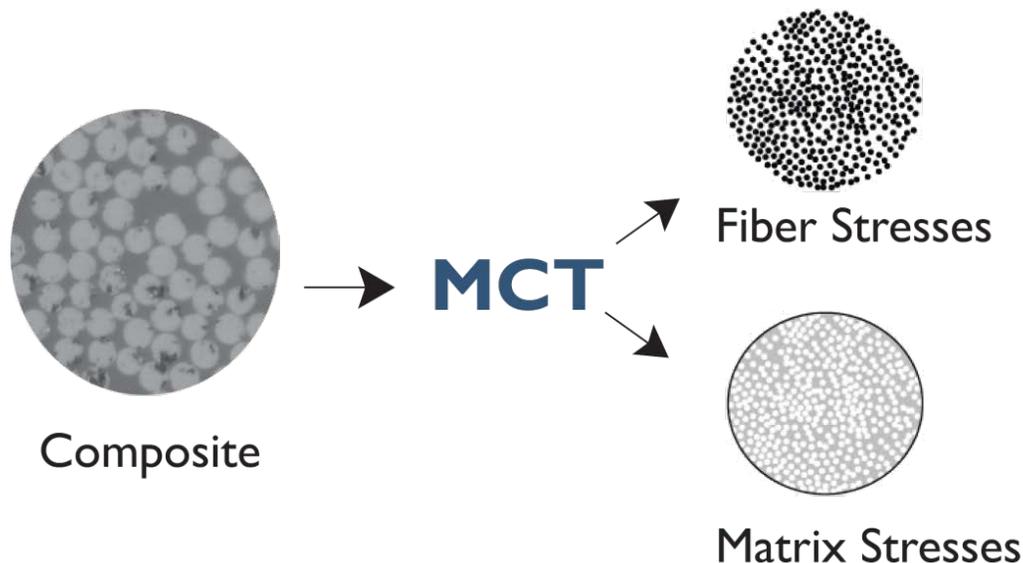


Figure 1: Multicontinuum Theory employs independent failure criteria for the constituent fiber and matrix elements of a composite material.

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

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. Autodesk Heliuss PFA 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 an Autodesk Heliuss PFA 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 criterion removes much guesswork from the analyst's 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. This initiates early on in the loading at 260% Flight Limit Load (FLL), but the structure does not collapse until 850% FLL! It can be seen in the table below that the results of analysis with Autodesk Helius PFA correspond favorably with the physical test results.



Figure 2. The Composite Adapter for Shared Payloads (CASPAR) and its simulation with Autodesk Helius PFA in Abaqus.

Table: Actual and Simulated Failure Loads

%FLL	Actual Failure Event	%FLL	Autodesk Helius PFA 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 (in the plot below) 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, Autodesk Helius PFA 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 (black dotted line).

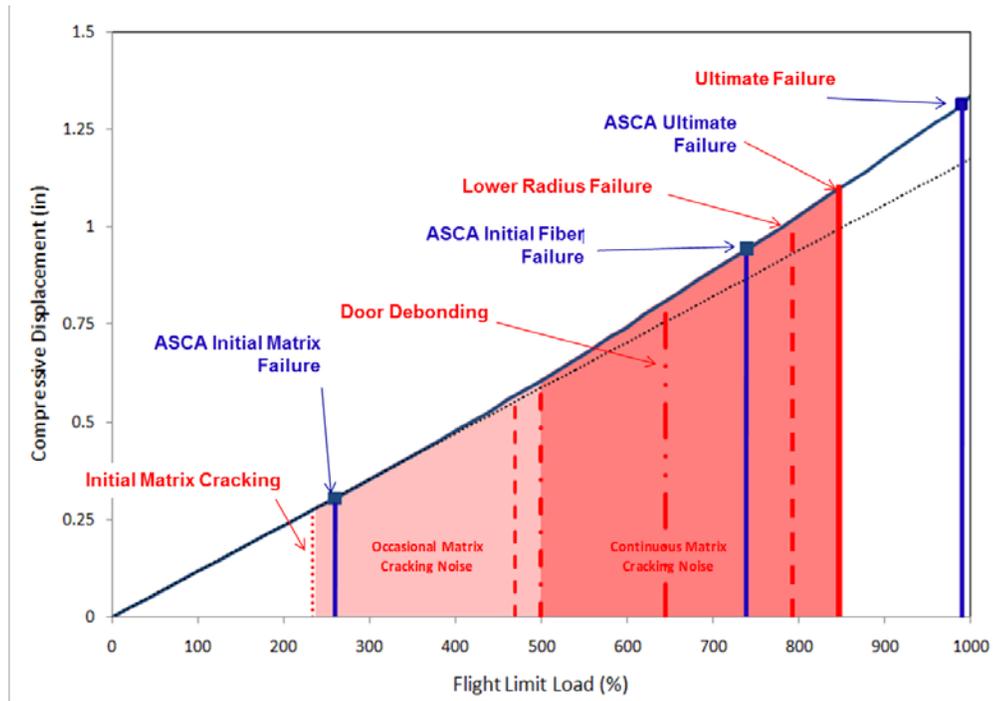


Figure 3: Analysis vs. test results demonstrate Autodesk Heliuss PFA closely predicts discrete failure events and nonlinear behavior.

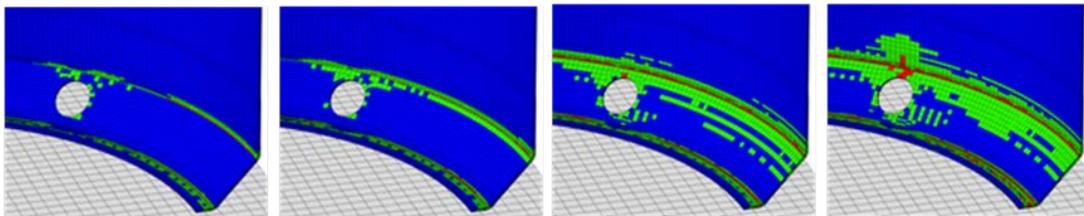
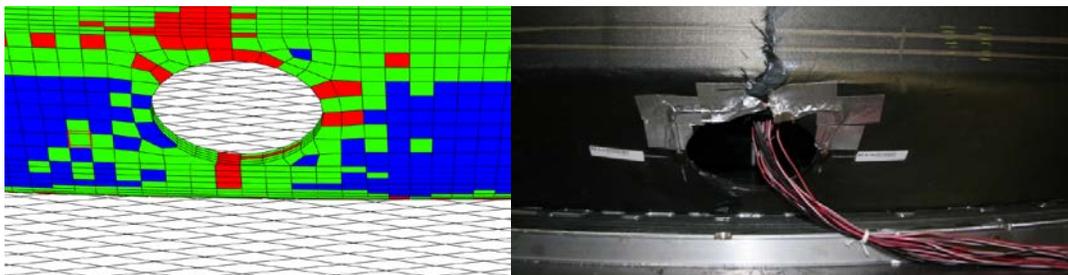


Figure 4: Autodesk Heliuss PFA results showing progressive failure of the lower, tapered radius of the CASPAR structure – Undamaged (blue) / Failed Matrix (green) / Failed Fibers (red)

Figure 4: 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

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, Autodesk has developed the Intelligent Discrete Softening Method (or IDS Method), which has been incorporated in Autodesk Heliuss PFA. By using the IDS Method, Heliuss PFA ensures a robust convergence in all loading scenarios.

The result is the ability to conduct full-scale structural analysis in a practical amount of time. In the case of the space structure above, a detailed model was created using 3-D layered solid elements. Using Heliuss PFA, the 122,000 element progressive failure simulation was completed in just 1.5 days on a desktop computer.

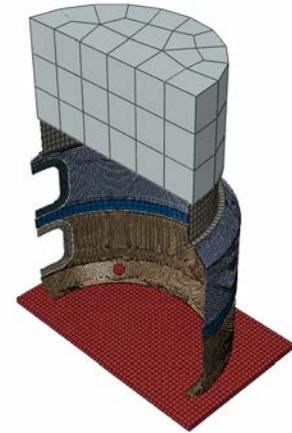


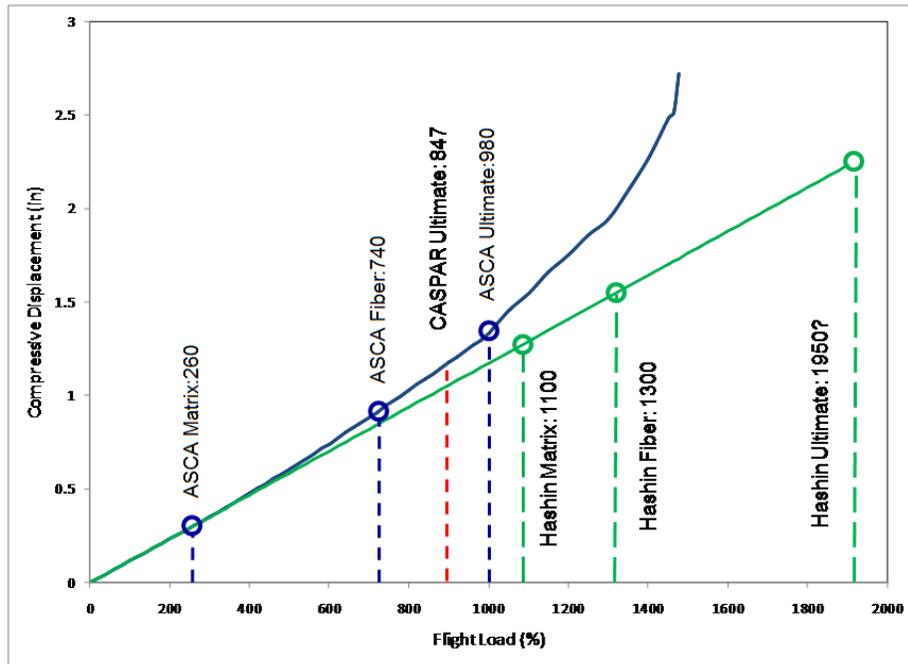
Figure 5: A softening method designed specifically for composites enables robust convergence.

How does this compare to other methods?

For comparison, let us look at how the analysis with Heliuss PFA 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 uses a composite average stress to do so and 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 will result in analytical solutions that are at least more than two times greater than the actual (experimental) failure.

Figure 6: ASCA (blue) prediction of nonlinear response vs. Hashin (green) linear-elastic



Implementation

Progressive Failure Made Real... And Easy!

Autodesk® Heliuss PFA was developed with the intent of improving the use of composites by enabling designers and engineers with an accurate, yet practical analysis tool. To that end, it incorporates these key elements in its implementation:

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

Autodesk Heliuss PFA 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 code. (Typically a layered element is used to resolve laminate stresses into lamina stresses. From there, the Autodesk Heliuss PFA code is called at each material point to supply constitutive information to the solver.)

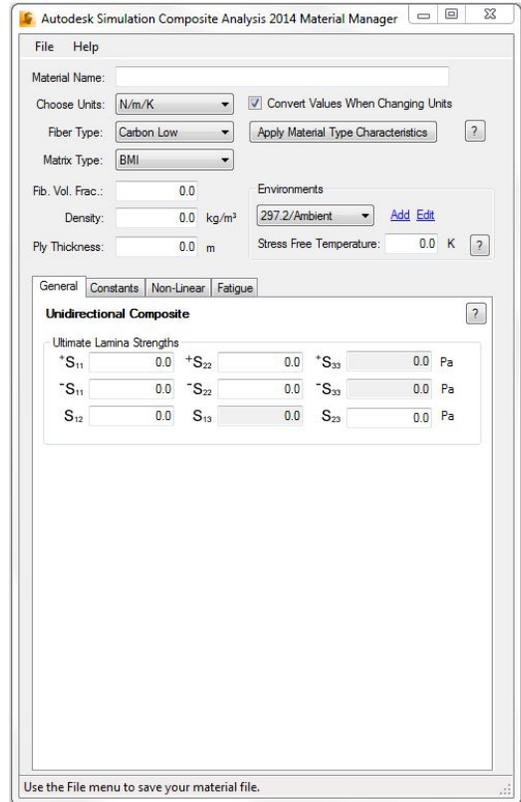
- **Material characterization must use only standard input parameters**

Characterization and qualification of a composite material 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 precluding many of the advantages of composites. Variations in manufacturing lead to the 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.

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 ASCA approach has been specifically designed to require only these standard material inputs.*



- **Computational efficiency is paramount**

Excessive run times measured in weeks do not fit with most 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 are 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 the progressive failure analysis are gone

The days of adjusting for inaccurate answers or coping with the inability to reach a solution are over. Helius PFA delivers a solution that can put advanced composite analysis technology feasibly into the hands of structural designers and analysts. It has been developed so that the headaches and time loss are eliminated from progressive failure analysis of composites - making progressive failure doable, believable ... and easy.

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