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THE MCT MULTISCALE MATERIAL CHARACTERIZATION PROCESS

Characterizing microscale interactions using lamina properties.

Firehole Composites

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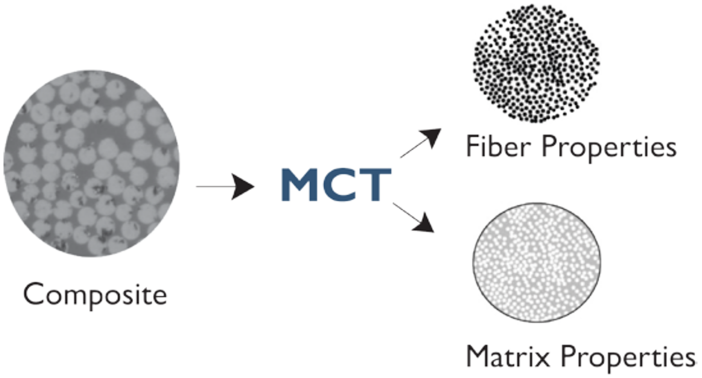


INTRODUCTION

The challenge in producing a composite analysis solution that is both accurate and useful is to develop a method that provides the insight of multiscale analysis, but that is practical for industry use.

Two key fundamentals of Helius:MCT are:

1. It employs Multicontinuum Technology, which extracts the constituent (fiber and matrix) average stresses from the composite average stress, and applies distinct failure criteria to each.
2. It requires only standard test data, making it practical and efficient.

The following paper describes the process by which the combination of these two is achieved. It includes excerpts from the Helius:MCT Theory Manual.

THE PROBLEM

Accurate Modeling Requires Multiscale Analysis

Multiscale stress and strain information is necessary to capture the failure response of the constituents in a composite.

Failure in composite laminates begins at the microstructure level. It occurs via the progression of constituent-level events including local matrix failure, matrix failure propagation, local fiber failure, fiber failure propagation and ultimate failure. Each of these events must be captured in order to achieve an accurate failure simulation of a composite.

To accurately account for the contributions of the fiber and matrix, an analysis must capture microstructural information where failure initiates. Indeed, many researchers have recognized the need for multiscale stress or strain information in order to accurately capture the failure response of the constituents in a composite [1] [2] [3]. Once the stress of the constituent is known, the appropriate failure criteria can be applied.

Achieving Accuracy with Practical, Meaningful Material Characterization

Material characterization is a critical yet often overlooked contributor to reliable failure simulation — the result is only as accurate as the input parameters.

Many new multiscale approaches require the use of non-standard material parameter, making them difficult to use.

Many recently developed multiscale failure theories require the use of amplification factors, a priori fracture information, or exotic material parameters [1] [8]. Such parameters can only be derived from expensive and time consuming test methods that have not been widely accepted by the testing community or vetted as standard test methods. Sometimes these parameters may be estimated by expert theoretical work, but an analyst working in industry is not often afforded the luxury of intimate theoretical knowledge. In practice, parameters are often chosen by mere conjecture, leading to further uncertainty in analytical prediction.

Material characterization and qualification is an expensive and time consuming process. A useful analysis solution would require only readily available material inputs derived from standard testing methods

THE SOLUTION: MCT MULTISCALE MATERIAL CHARACTERIZATION PROCESS

Helius:MCT employs an efficient method for accessing stresses in the fiber and matrix constituents of a composite. It is based on Multicontinuum Theory (MCT), which extracts fiber and matrix constituent level stress/strain fields from lamina stress/strain fields. Individual failure criteria for the fiber and matrix constituents are then used based on their respective constituent stress fields [6] [7]. The following will show how Helius:MCT conducts this analysis using only standard material properties for the composite and constituent materials, providing a solution that is accurate and practical.

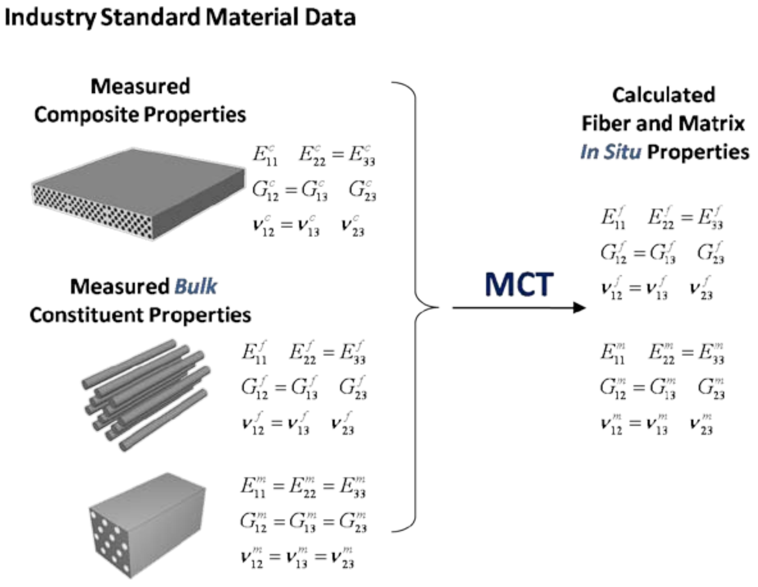
Standard material inputs for a transversely isotropic composite are the elastic constants E_{11}, E_{22}, ν_{12}, $\nu_{23,}$ G_{12}, and the tensile and compressive strengths S_{11}, S_{22} and the shear strengths S_{12} and S_{23}. These can readily be determined from relatively inexpensive coupon testing or, in many cases, handbook [9] values for unidirectional lamina. The MCT approach has been specifically designed to require only these standard material inputs.

In Situ Constituent Properties

The MCT material characterization process determines constituent properties that cause a micromechanical FE model to behave like the measured composite properties.

Before Helius:MCT can be used to model the response of a particular composite material, the composite material must first be subjected to the MCT material characterization process. This process consists of determining a set of constituent properties that cause a micromechanical finite element model to behave elastically like the measured composite properties.

In order to perform the MCT material characterization, measured elastic moduli and measured Poisson ratios of the composite material are utilized to iteratively determine the *in situ* moduli and *in situ* Poisson ratios of the individual constituent materials (fiber and matrix).



What are "Bulk" and "In Situ" Constituent Properties?

Before proceeding with a detailed discussion of the MCT material characterization process, it is informative to explain the difference between *bulk* constituent properties and *in situ* constituent properties and to explain why *in situ* constituent properties are necessary in the MCT material characterization process.

"Bulk" constituent properties are measured using homogeneous test specimens of the constituent material.

Bulk constituent properties are simply properties that are measured using homogeneous test specimens composed of a single constituent material. Generally speaking, a micro-mechanical finite element model that uses *bulk* constituent properties will *not* yield accurate homogenized properties for the composite material. The inability of the micro-mechanical finite element model to predict accurate homogenized properties for the composite material is the result of several different factors that are described below.

1) The micro-mechanical finite element model represents an *idealized* microstructure, not the *actual* microstructure.
    a) In an actual composite material that has a fiber volume fraction of ϕ_f, the fibers exhibit a random distribution with local regions where fibers are actually touching each other and other regions where the distance between fibers is relatively large. Even if we attempt to use a micro-mechanical finite element model with random fiber spacing, it is doubtful that the model correctly reflects the same degree of randomness exhibited in the actual composite material.
    b) The actual composite material will typically have a characteristic distribution of various types of defects at the micro-structural level caused by the manufacturing and curing processes. In practice, the micro-mechanical finite element model is assumed to be completely free of these micro-defects.

2) Knowledge of the mechanical and thermal properties of the fiber/matrix *interphase* region is most often completely lacking; therefore, the stiffness of the interphase is not explicitly accounted for in the micro-mechanical finite element model.

3) Even if the bulk matrix properties are based on precise measurements performed on bulk matrix material, it is unlikely that the bulk matrix material has been subjected to the identical cure conditions (e.g., temperature, pressure, deformation, chemical environment) as the same matrix material experiences in a fiber-reinforced composite laminate. Therefore, we expect that these differences in curing conditions will cause the resin in the composite material to behave somewhat differently from the bulk resin material.[10]

4) Knowledge of the bulk mechanical and thermal properties of the fiber and matrix constituents is typically *incomplete*. In practice, some of the bulk constituent properties are actually *measured*; some of the bulk constituent properties are *estimated* based on measurements from similar materials, and still other bulk constituent properties are simply guessed.

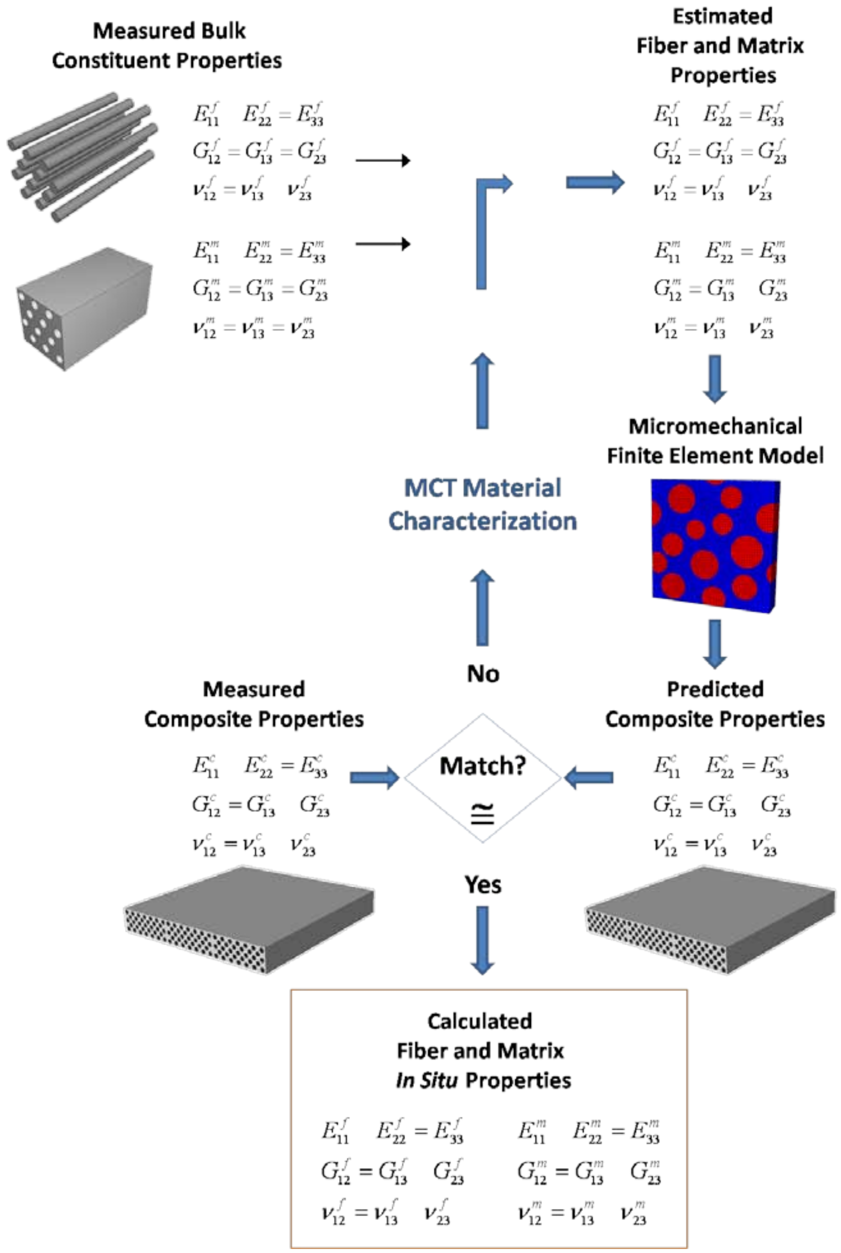
To account for the discrepancies between bulk constituent properties and the resultant homogenized properties for the composite material, MCT methodically adjusts the constituent properties to determine in situ *properties for the specific material.*

One way of collectively accounting for all of the discrepancies and uncertainties listed above in items 1 through 4 is to use *altered constituent properties* (instead of measured bulk constituent properties) that cause the micro-mechanical finite element model to produce the elastic properties that were actually measured for the composite material (e.g., stiffness, Poisson effect, and thermal expansion). These *altered* constituent properties are referred to as *in situ* constituent properties to emphasize that the properties are purposefully chosen to function correctly in a specific micro-mechanical finite element model of a specific composite material, causing the finite element model to yield the measured composite properties. Thus, the concept of developing *in situ* constituent properties can be thought of as purposefully tuning one aspect of the micro-mechanical finite element model (i.e., the material properties) to compensate for all of the other errors and unknowns in the micro-mechanical finite element model.

Determining the In Situ Constituent Properties

The process of determining the *in situ* constituent properties is a mathematical optimization problem where we begin with the bulk constituent properties and iteratively adjust these properties so that we minimize the error between the measured composite properties and the predicted composite properties of the micro-mechanical finite element model. Consequently, standard optimization routines are utilized to determine the in situ constituent properties. This optimization is currently performed using the method of steepest descent. It is assumed that each of the tensile moduli is equal to the corresponding compressive moduli.

To determine in situ constituent properties, we begin with the bulk constituent properties and iteratively adjust them to minimize the error between the measured composite properties and the predicted composite properties of the micro-mechanical FE model.



During the optimization of the *in situ* constituent properties, both the matrix and fiber constituents are assumed to be transversely isotropic materials. To begin the optimization process, the initial values of the *in situ* constituent properties are provided by the measured bulk constituent properties. The *in situ* constituent properties are chosen so that the homogenized composite properties (predicted by the micro-mechanical finite element model) agree with the eight measured composite properties in a weighted least-squares sense. The current implementation of the material characterization process uses equal weighting of E_{11}, E_{22}, G_{12}, G_{23}, and ν_{12}.

Example Problem

As an example, we shall determine the *in situ* properties for a glass fiber reinforced polyester (D155/CoRezyn®63-AX-051 OrthoPolyester).

Generally, our confidence in the measured value of G^c_{23} is not high, so we will exclude using this term in minimizing the error. This is accomplished by setting the "weight" of this term in the error calculation to zero.

Measured Composite Properties of D155/CoRezyn®63-AX-051OrthoPolyester**:**

Fiber volume fraction $\phi_f = 0.36$

$E^c_{11} = 28.3\text{GPa}, \quad E^c_{22} = E^c_{33} = 7.75\text{GPa}$

$G^c_{12} = G^c_{13} = 3.3\text{GPa}, \quad G^c_{23} = 2.55\text{GPa}$

$\nu^c_{12} = \nu^c_{13} = 0.32, \quad \nu^c_{23} = 0.44$

Measured bulk matrix properties for CoRezyn®63-AX-051OrthoPolyester
(or *initial* values of the in situ matrix properties):

$E^m_{11} = E^m_{22} = E^m_{33} = 3.8\text{GPa}$

$G^m_{12} = G^m_{13} = G^m_{23} = 1.407\text{GPa}$

$\nu^m_{12} = \nu^m_{13} = \nu^m_{23} = 0.35$

Measured bulk fiber properties for D155 glass fiber (or *initial* values of the in situ fiber properties):

$E^f_{11} = E^f_{22} = E^f_{33} = 74.\text{GPa}$

$G^f_{12} = G^f_{13} = G^f_{23} = 30.8\text{GPa}$

$\nu^f_{12} = \nu^f_{13} = \nu^f_{23} = 0.2$

If the micro-mechanical finite element model is used in conjunction with the measured bulk constituent properties, then the following composite properties are predicted:

Measured Composite Properties	**Predicted Composite Properties**	**Percent Difference**
$E^c_{11} = 28.3\text{GPa}$	$E^c_{11} = 29.0\text{GPa}$	2.47%
$E^c_{22} = E^c_{33} = 7.75\text{GPa}$	$E^c_{22} = E^c_{33} = 7.62\text{GPa}$	1.67%
$G^c_{12} = G^c_{13} = 3.3\text{GPa}$	$G^c_{12} = G^c_{13} = 2.79\text{GPa}$	15.45%
$G^c_{23} = 2.55\text{GPa}$	$G^c_{23} = 2.63\text{GPa}$	3.14%
$\nu^c_{12} = \nu^c_{13} = 0.32$	$\nu^c_{12} = \nu^c_{13} = 0.288$	10.0%
$\nu^c_{23} = 0.44$	$\nu^c_{23} = 0.451$	2.5%

The optimization procedure produces the following *in situ* constituent properties.

Optimized *in situ* matrix properties:

$E^m_{11} = 3.8\text{GPa}$, $E^m_{22} = E^m_{33} = 3.75\text{GPa}$

$G^m_{12} = G^m_{13} = 1.681\text{GPa}$, $G^m_{23} = 1.403\text{GPa}$

$\nu^m_{12} = \nu^m_{13} = 0.393$, $\nu^m_{23} = 0.335$

Optimized *in situ* fiber properties:

$E^f_{11} = 72.1\text{GPa}$, $E^f_{22} = E^f_{33} = 72.1\text{GPa}$

$G^f_{12} = G^f_{13} = 31.2\text{GPa}$, $G^f_{23} = 31.2\text{GPa}$

$\nu^f_{12} = \nu^f_{13} = 0.219$, $\nu^f_{23} = 0.219$

Using the optimized in situ constituent properties in conjunction with the micro-mechanical finite element model yields the following predicted composite properties.

Measured Composite Properties	**Predicted Composite Properties**	**Percent Difference**
$E^c_{11} = 28.3\text{GPa}$	$E^c_{11} = 28.3\text{GPa}$	0.00%
$E^c_{22} = E^c_{33} = 7.75\text{GPa}$	$E^c_{22} = E^c_{33} = 7.77\text{GPa}$	0.26%
$G^c_{12} = G^c_{13} = 3.3\text{GPa}$	$G^c_{12} = G^c_{13} = 3.29\text{GPa}$	0.30%
$G^c_{23} = 2.55\text{GPa}$	$G^c_{23} = 2.64\text{GPa}$	3.53%
$\nu^c_{12} = \nu^c_{13} = 0.32$	$\nu^c_{12} = \nu^c_{13} = 0.321$	0.31%
$\nu^c_{23} = 0.44$	$\nu^c_{23} = 0.47$	6.82%

Notice that, in general, the use of optimized *in situ* constituent properties (as opposed to measured bulk constituent properties) causes the micro-mechanical finite element model to predict homogenized composite properties that agree much more closely with the actual measured composite properties. Of the six measured composite properties (E^c_{11}, $E^c_{22} = E^c_{33}$, $G^c_{12} = G^c_{13}$, G^c_{23}, $\nu^c_{12} = \nu^c_{13}$, ν^c_{23}), G^c_{23} and ν^c_{23} are the only properties that exhibit less agreement with the measured values after completing the optimization process. This increased discrepancy between the measured and predicted values of G^c_{23} and ν^c_{23} is simply caused by the fact that these two values were assigned weight coefficients of *zero*, thus preventing these two properties from participating in the optimization process. The reason for this choice was that generally measured values of G^c_{23} and ν^c_{23} are considered to be significantly less accurate than the other composite properties due to the difficulty in performing the experiment to determine these values (hence the reason for a *weighted* optimization).

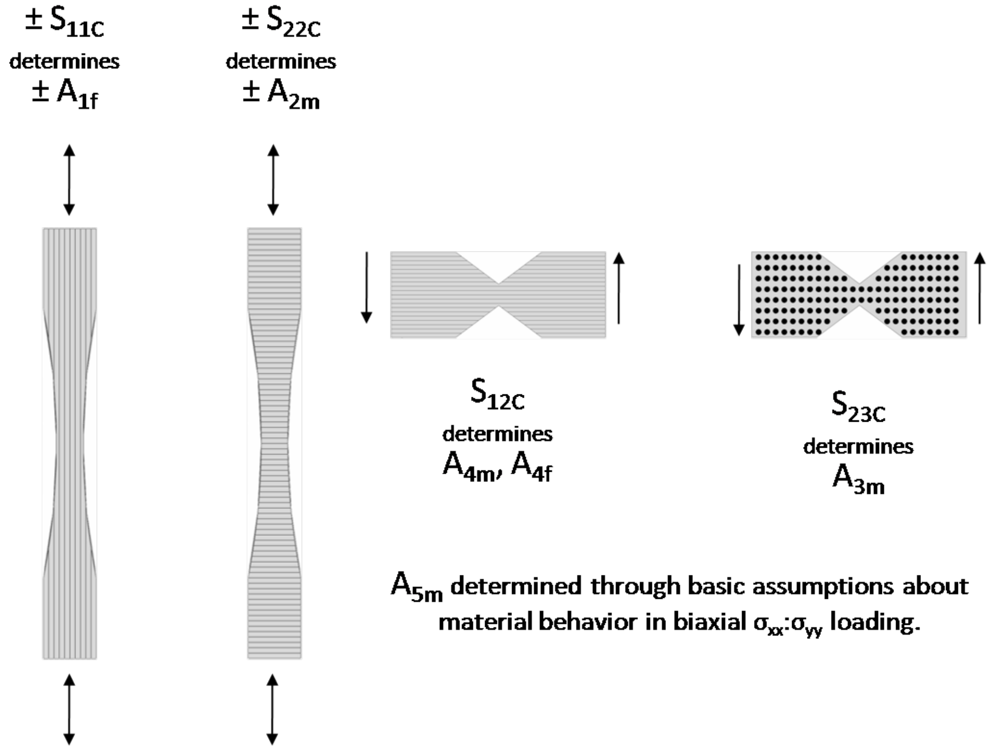
Failure Coefficient Determination

Distinct failure criteria are applied to the fiber and matrix using coefficients determined from standard composite strength data.

The second aspect of the material characterization process is determining strength parameters for both the fibers and matrix. Failure criteria are applied to separately to the fiber and matrix, the coefficients for each must be determined. This is done using a combination of the standard composite lamina strength data, the tensile and compressive strengths S_{11}, S_{22} and the shear strengths S_{12} and S_{23}, the in situ material characterization described above and some basic assumptions about the behaviour of the composite. For example fiber failure parameter A_{1f} is determined from longitudinal tension/compression data in conjunction with the MCT decomposition. Under longitudinal tension/compression, the fiber stress state is near one-dimensional leading to the result

$$^{\pm}A_{1f} = \frac{1}{^{\pm}S^{2}_{11m}} \quad ,$$

where $^{\pm}S_{11f}$ is the fiber axial stress at composite failure in tension and compression, respectively. A similar process is followed for each of the failure coefficients. The details of the process can be found in Nelson, Hanson, and Mayes [7].



IMPLEMENTATION

As illustrated above, the multiscale analysis approach embedded in Helius:MCT requires characterization of the constituent materials. This is done using measured material properties of the composite lamina and homogeneous "bulk" constituent materials. These standard material properties include the measured elastic moduli and measured Poisson ratios and composite lamina strength data .

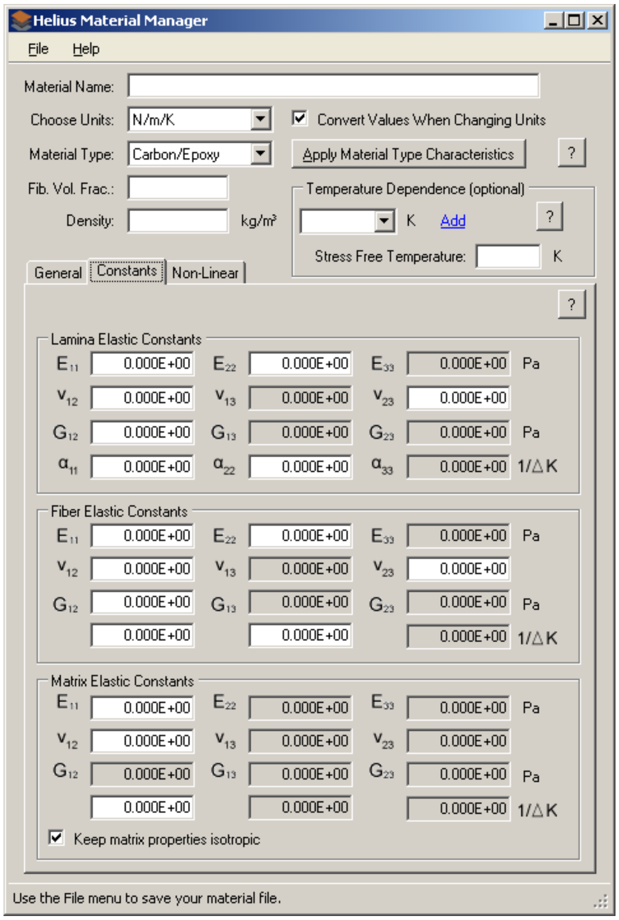
Helius Material Manager facilitates easy input of material properties required for MCT to characterize in situ properties and failure coefficients.

To enable easy input of these initial properties, Helius:MCT is available with a companion utility called Helius:Material Manager.

Using Helius Material Manager

The Helius Material Manager provides a convenient graphical user interface (GUI) for providing the composite and constituent material properties required for material characterization as described above. The Material Manager then creates the material file required to execute a Helius:MCT analysis.

Helius Material Manager guides the user in entering lamina and constituent elastic material properties to be used in the MCT material



Material Name:

Choose Units: N/m/K

☑ Convert Values When Changing Units

Material Type: Carbon/Epoxy

Fib. Vol. Frac.:

Density: kg/m³

Temperature Dependence (optional): K

Stress Free Temperature: K

Lamina Elastic Constants

E_{11}	0.000E+00	E_{22}	0.000E+00	E_{33}	0.000E+00	Pa
v_{12}	0.000E+00	v_{13}	0.000E+00	v_{23}	0.000E+00	
G_{12}	0.000E+00	G_{13}	0.000E+00	G_{23}	0.000E+00	Pa
α_{11}	0.000E+00	α_{22}	0.000E+00	α_{33}	0.000E+00	1/ΔK

Fiber Elastic Constants

E_{11}	0.000E+00	E_{22}	0.000E+00	E_{33}	0.000E+00	Pa
v_{12}	0.000E+00	v_{13}	0.000E+00	v_{23}	0.000E+00	
G_{12}	0.000E+00	G_{13}	0.000E+00	G_{23}	0.000E+00	Pa
	0.000E+00		0.000E+00		0.000E+00	1/ΔK

Matrix Elastic Constants

E_{11}	0.000E+00	E_{22}	0.000E+00	E_{33}	0.000E+00	Pa
v_{12}	0.000E+00	v_{13}	0.000E+00	v_{23}	0.000E+00	
G_{12}	0.000E+00	G_{13}	0.000E+00	G_{23}	0.000E+00	Pa
	0.000E+00		0.000E+00		0.000E+00	1/ΔK

☑ Keep matrix properties isotropic

Use the File menu to save your material file.

The Standard Lamina Material Properties

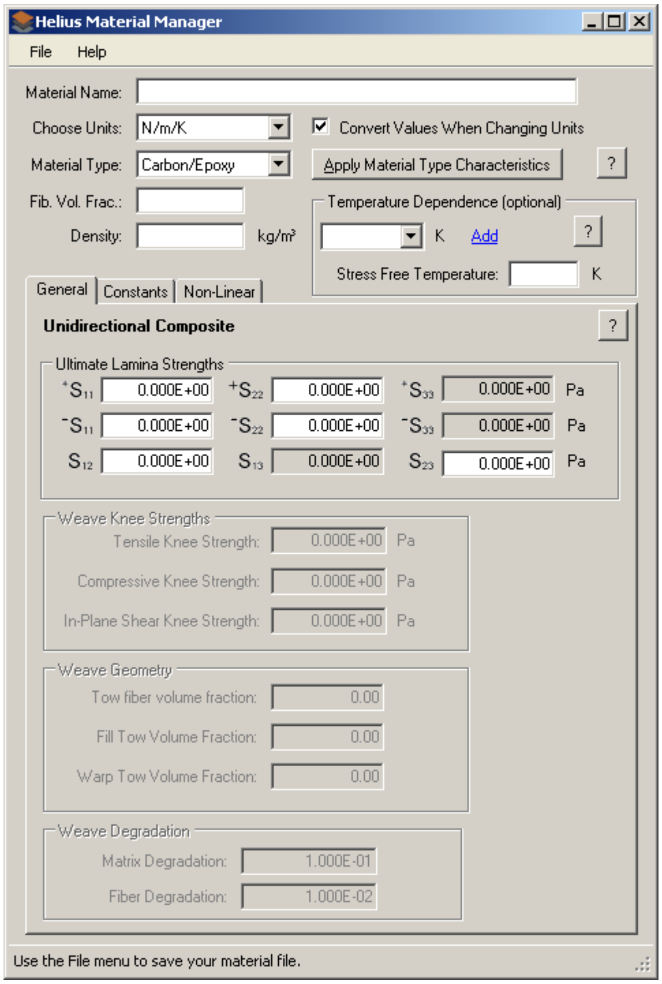
Helius:MCT treats the lamina, fiber, and matrix as transversely isotropic. Fields in white are populated as follows:

- E_{11} (required): Young's modulus of lamina in fiber direction.
- E_{22} (required): Young's modulus of lamina in transverse direction. (This modulus will be equivalent to the E_{33} modulus)
- v_{12} (required): In-plane Poisson ratio. (This ratio will be equivalent to the v_{13} modulus)
- v_{23} (required): Interlaminar Poisson ratio. (Note: Even if the model is made up of shell elements, v_{23} is still required for a Helius:MCT analysis)
- G_{12} (required): In-plane lamina shear modulus. (This modulus will be equivalent to the G_{13} modulus)

Note: G_{23} is calculated via Equation 1:

$$G_{23} = \frac{E_{22}}{2(1+\nu_{23})} \qquad (1)$$

Helius Material Manager guides the user entering lamina strength properties to be used in the determination of fiber and matrix strength parameters.



Material Name:

Choose Units: N/m/K

☑ Convert Values When Changing Units

Material Type: Carbon/Epoxy

Fib. Vol. Frac.:

Density: kg/m³

Temperature Dependence (optional): K

Stress Free Temperature: K

Unidirectional Composite

Ultimate Lamina Strengths

$^+S_{11}$	0.000E+00	$^+S_{22}$	0.000E+00	$^+S_{33}$	0.000E+00	Pa
$^-S_{11}$	0.000E+00	$^-S_{22}$	0.000E+00	$^-S_{33}$	0.000E+00	Pa
S_{12}	0.000E+00	S_{13}	0.000E+00	S_{23}	0.000E+00	Pa

Weave Knee Strengths

Tensile Knee Strength: 0.000E+00 Pa

Compressive Knee Strength: 0.000E+00 Pa

In-Plane Shear Knee Strength: 0.000E+00 Pa

Weave Geometry

Tow fiber volume fraction: 0.00

Fill Tow Volume Fraction: 0.00

Warp Tow Volume Fraction: 0.00

Weave Degradation

Matrix Degradation: 1.000E-01

Fiber Degradation: 1.000E-02

Use the File menu to save your material file.

The Standard Lamina Strengths

Helius:MCT treats the lamina as transversely isotropic. If the material data the user wishes to enter is not transversely isotropic, the user should contact Firehole Technologies to arrive at a solution.

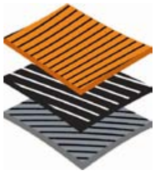
- $^+S_{11}$ (required): Tensile lamina strength in the fiber direction.
- $^+S_{22}$ (required): Tensile lamina strength in the transverse direction. (This strength will be equivalent to the $^+S_{33}$ strength)
- $^-S_{11}$ (required): Compressive lamina strength in the fiber direction.
- $^-S_{22}$ (required): Compressive lamina strength in the transverse direction. (This strength will be equivalent to the $^-S_{33}$ strength)
- S_{12} (required): Longitudinal shear strength of the lamina. (This strength will be equivalent to the S_{13} strength)

S_{23} (required if using solid elements, optional if using shell elements – if using shell elements and a value is entered, it will be neglected so the value may be left as 0): Transverse shear strength of the lamina.

SUMMARY – THE HEADACHES OF COMPOSITE PROGRESSIVE FAILURE ANALYSIS ARE GONE

Helius:MCT has been designed with the composites engineer in mind. It has been developed such that it not only provides more accurate answers for composite analysis, but does so in a way that is practical and efficient. Equipped simply with standard material data, the designer or analyst is able to arrive at *in situ* properties for the fiber and matrix of a particular composite. These *in situ* properties allow the use of Helius:MCT, which yields constituent-level stress resolution for state-of-the-art accuracy in composite analysis.

To learn more about the Helius:MCT composite analysis solution, visit us at www.firehole.com or call us at 1.307-460-4763.



ABOUT FIREHOLE COMPOSITES

Firehole Composites provides innovative software tools and engineering services designed to significantly improve structural design and analysis with composite materials. Their mission is to help engineers create lighter, stronger, safer and more efficient composite designs through superior analysis capability. Firehole's team of engineers has extensive study and experience in analysis of composite materials and is well-skilled in software development. For more information, visit www.firehole.com.

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