SALOME-MECA Composite Designer plugin: post processing methods

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Introduction

In contrary to other FEA solvers like Abaqus, Code-Aster reports by default the stress components in the global coordinate system of the problem X,Y,Z.
The stress components in both orthotropic shells and solids need thus to be transformed to the appropriate local material coordinate system to calculate local orthotropuc failure criteria.
In Code-Aster the stress components available are either SIXX, SIYY, SIXY for 2D plane stress tensors in shell layers or SIXX, SIYY, SIZZ, SIXY, SIXZ, SIYZ for 3D stress tensors in solids.

Post processing in Composite Designer plugin

The first role of Composite Designer plugin is to help the user to generate a proper Code-Aster FE model description for multilayer shells and orthotropic solids. Thus the first part of Composite Designer aims at generating a template command file that defines the materials (orthotropic elastic,layup), element properties definition (orientation, thickness, layup/material) and a basic set of load case and solution options that need to be adapted by the end user in the AsterStudy module of Salome Meca. In principle, after generating the model .comm file, the user should only need to edit the load case to have a complete simulation.

However, after the solution of the static problem, the main question is how to evaluate the stresses and more importantly the failure indicators for the composite structure. For this task, Composite Designer helps the end user by generating a consistent post processing command file to automate the following tasks :

1. Transforming the fields to local coordinate systems for shells and orthotropic solid regins
2. Extract stress state in each ply of a multilayer shell
3. Compute failure criteria for each ply
4. Compute the maximum “through thickness” failure index (max among the plies)
5. Compute 3D failure criteria for solid regions

WARNING : the post processing script generated by Composite Designer MUST be regenerated after any change to the materials, layup definitions, material orientation or assignments. Failure to update the post processing script may result in complementally wrong failure criteria.

This is since the script is using hard coded parameter properties and angles and thus is not dynamically adapting to the model definition.

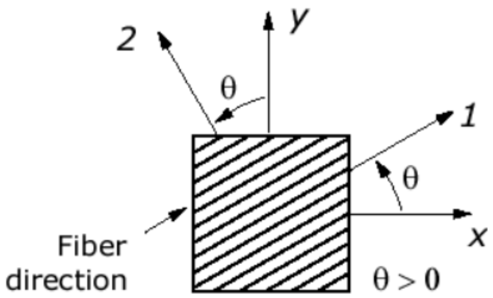
Stress transformation and failure criteria for shells

There are multiple options to compute stresses in a given orientation in a shell using Code-Aster.
The chosen implementation uses a Code-Aster FORMULE (Python expression) to implement the calculation of rotated stress components as follows:

Formulas for local ply-level stresses in material coordinate system (example for theta=-45°):

```
S11 = FORMULE(
  NOM_PARA=('SIXX', 'SIYY', 'SIXY'),
  VALE='SIXX*cos(-45.0/180.0*pi)**2 + SIYY*sin(-45.0/180.0*pi)**2 + SIXY*2*cos(-
```

```
45.0/180.0*pi)*sin(-45.0/180.0*pi)'
)
S22 = FORMULE(
  NOM_PARA=('SIXX', 'SIYY', 'SIXY'),
  VALE='SIXX*sin(-45.0/180.0*pi)**2 + SIYY*cos(-45.0/180.0*pi)**2 - SIXY*2*cos(-
45.0/180.0*pi)*sin(-45.0/180.0*pi)'
)
S12 = FORMULE(
  NOM_PARA=('SIXX', 'SIYY', 'SIXY'),
  VALE='SIXX*-1*sin(-45.0/180.0*pi)*cos(-45.0/180.0*pi) + SIYY*sin(-45.0/180.0*pi)*cos(-
45.0/180.0*pi) +SIXY*(cos(-45.0/180.0*pi)**2 - sin(-45.0/180.0*pi)**2)'
)
```



If we define the coordinate transformation matrix as

$$[T]=\begin{bmatrix} \cos^2\theta & \sin^2\theta & 2\sin\theta\cos\theta \\ \sin^2\theta & \cos^2\theta & -2\sin\theta\cos\theta \\ -\sin\theta\cos\theta & \sin\theta\cos\theta & \cos^2\theta-\sin^2\theta \end{bmatrix}$$

and

$$[T]^{-1}=\begin{bmatrix} \cos^2\theta & \sin^2\theta & -2\sin\theta\cos\theta \\ \sin^2\theta & \cos^2\theta & 2\sin\theta\cos\theta \\ \sin\theta\cos\theta & -\sin\theta\cos\theta & \cos^2\theta-\sin^2\theta \end{bmatrix}$$

The coordinate transform of plane stress can be written in the following matrix form:

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_{xy} \end{Bmatrix} = [T]^{-1} \begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_{12} \end{Bmatrix}$$

Reference images eFunda.com : transformation matrix T to SIXX,SIYY,SIXY => SI11, SI22, SI33

Basic Implementation of HASHIN criteria in multilayer shells using Code-Aster FORMULE (Hashin model 1980, with alpha=1.0)

Definitions:

trick for positive / negative “bracket” values:

0.5*(x+abs(x)) = x if x>0; elset 0;

0.5*(x-abs(x)) = x if x <=0, else 0

note: XC, YC must be NEGATIVE !

Fiber tensile FT criterion

$$F_f^t = \left(\frac{\widehat{\sigma}_{11}}{X^T}\right)^2 + \alpha\left(\frac{\hat{\tau}_{12}}{S^L}\right)^2.$$

(for positive S11)

CritFt = (0.5* (S11+abs(S11)) / XT)**2 + (S12 / SL)**2

Fiber compression FC criterion

Fiber compression $(\widehat{\sigma}_{11} < 0)$:

$$F_f^c = \left(\frac{\widehat{\sigma}_{11}}{X^C}\right)^2.$$

CritFc= (0.5 * (S11-abs(S11)) / XC)**2

Matrix tension MT criterion

Matrix tension $(\widehat{\sigma}_{22} \geq 0)$:

$$F_m^t = \left(\frac{\widehat{\sigma}_{22}}{Y^T}\right)^2 + \left(\frac{\hat{\tau}_{12}}{S^L}\right)^2.$$

CritMt = (0.5* (S22+abs(S22)) /YT)**2 + (S12/SL)**2

Matrix compression MC criterion

Matrix compression $(\widehat{\sigma_{22}} < 0)$:

$$F_m^c = \left(\frac{\widehat{\sigma}_{22}}{2S^T}\right)^2 + \left[\left(\frac{Y^C}{2S^T}\right)^2 - 1\right]\frac{\widehat{\sigma}_{22}}{Y^C} + \left(\frac{\hat{\tau}_{12}}{S^L}\right)^2.$$

Hypothesis Hashin 1980 model :

ST = YC/2 => F_MC= (S22/YC)**2 + [0]*S22/YC +(S12/SL) ** 2 =>

CritMc = (0.5*(S22-abs(S22)) / YC)**2 + (S12/SL)**2

Modified failure indicators to linearize the criterion

The Hashin failure criteria are 2nd order functions of stresses and thus the failure indicators are not linear which make it more difficult to estimate an actual safety factor (linear load factor to failure). To simplify the estimation of the safety factor, the Hashin criteria can be approximately linearized for simpler interpretation.

Thus **Composite Designer computes the LINEARIZED FAILURE INDICATORS as follows**:

Linearized CritFT = sqrt(CritFT)

in this way, the criterion becomes roughly proportional to load (not exactly as all terms are not quadratic) while the critical state is still reached when the indicator is exactly equal to 1.0.

It is easier to interpret the results as for example:

- if we were using the classical quadratic Hashin criterion with a value of FT = 0.5, it would mean that the load can be increased approximately by 1/sqrt(0.5) = 1/0.707 to reach failure. Or if Hashin criterion was 2.0, this would mean that load should be reduced by sqrt(2.0) to prevent failure.
- using a linearized criterion would lead to a Linearized CritFT = sqrt(0.5) = 0.707; thus indicating approximately 30% margin on the load, while a Linearzed CritFT = sqrt(2.0)=1.414 indicates directly an approximate 41% overload.

Ply level stresses and failure criteria output for multilayer shells:

UT01_ELGA field

Available as results ply by ply, in result Rxx_yy where xx = regionId and yy = ply number. Note that numbering starts at 0. For example: R2_3 contains the results of the 4^{th} ply of the 3^{rd} shell region.

Components:

X1 = S11 = stress along material dir 1 (= fibers usually)
X2 = S22 = stress along mat. Dir 2 (= transverse in plane usually)
X3 = S12 (in plane shear stress, note : there is not interlaminar shear in DKT formulation…)

Failure criteria

UT02_ELGA field

Available either:

1. as ply by ply output in Rxx_yy result sets
2. or compiled in FC_Rxx results using a pseudo time to represent the ply.
   Example:
   FC_R2 at time=1.004 = 4^{th} ply of shell region 2 (=3^{rd} shell region as numbering start at 0)
3. or combined in a single “maximum” output field named CritAll

Components:

X1= sqrt(CritFT) = linearized Hashin fiber tension criterion
X2= Sqrt(CritFC) = linearized Hashin fiber compression criterion
X3=Sqrt(CritMT) = linearized Hashin matrix tensile criterion
X4=Sqrt(CritMC)= linearized Hashin matrix compression criterion

Stress transformation and failure criteria for 3D solids

Stress transformation for Solids
Due to some annoying limitations of the MODI_REPERE command of Code-Aster that cannot process mixed Shell & Solid models, the stress state transformation from the global to local (orthotropic) material coordinate system are computed using Python formula.

Definition of local coordinate system by Yaw (alpha), Pitch (beta), Roll (gamma) angles, taken from Code-Aster AFFE_CARA_ELEM documentation:

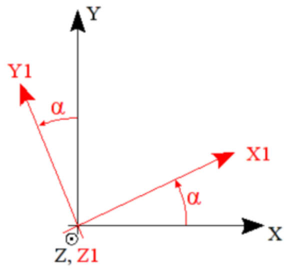


Figure 10.4-1 : angle α .

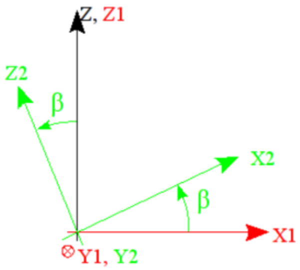


Figure 10.4-2 : angle β .

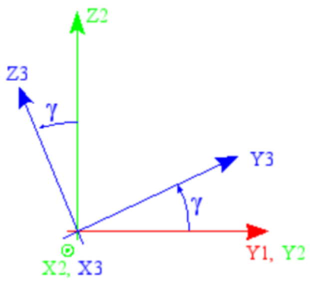


Figure 10.4-3 : angle γ .

Le repère local est : $(X_3 Y_3 Z_3)$

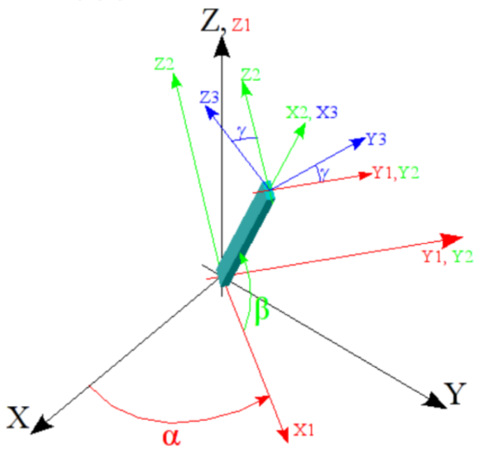


Figure 10.4-4 : Représentation des repères global et local.

3D FAILURE MODELS
Many models exist for damage / failure envelopes of composites but most criteria are formulated in plane-stress conditions (compatible with shell stress assumptions) and thus only include three components of stress in their prediction (SIXX,SIYY & SIXY). When modeling a composite using 3D solid elements, one cannot assume that the transverse normal stress is zero and depending on the orientation of the element and local coordinate system, the stress component SIZZ or SIXZ (& SIYZ) can become the critical stress components. To account for such effects, Composite Designer implements a 3D extension of the Hashin model.

The chosen failure criterion for 3D solids in Composite Designer is based on different sources.

The matrix failure criterion is based on the following Hashin 3D criterion derived from Hashin’s 1980 paper in Journal of Applied Mechanics. Some modifications have been implemented to account for different shear strength (S12 and S13) as well as different transverse strength Y, Z. Namely, the longitudinal shear strength Tau_A is calculated as the mean of S12 and S13 => Tau_A = 0.5 (S12+S13).

The transverse tensile or compressive strength YT or YC are calculated similarly as the mean YT & ZT , respectively YC & ZC.

The implemented criteria in Code-Aster Python “FORMULE” expression are linearized as mentioned previously and are as follows (SIXX,SIXY,... represent the local stress components in the material coordinate system) :

Fiber tension criterion (linearized), non null if SIXX >0:

FT=(SIXX+abs(SIXX))/(2*abs(SIXX)) * sqrt((SIXX / XT)**2 + (SIXY / S12)**2 + (SIXZ / S13)**2)

Fiber compression criterion (linearized), non null if SIXX <0 :

FC=(abs(SIXX)-SIXX)/(2*abs(SIXX)) * sqrt((SIXX / XC)**2)

Matrix tension criterion (linearized), non null if SIYY+SIZZ >0 :

MT=(abs(SIYY + SIZZ)+(SIYY+SIZZ))/(2*abs(SIYY+SIZZ)) * sqrt(((SIYY+SIZZ) / (0.5*(YT+ZT)))**2 + (SIYZ**2-SIYY*SIZZ)/((S23)**2) + (SIXY**2 + SIXZ**2)/ ((0.5 * (S12+S13))**2))

Matrix compression criterion (linearized), non null if SIYY+SIZZ <0 :

MC=(abs(SIYY + SIZZ)-(SIYY+SIZZ))/(2.0*abs(SIYY+SIZZ)) * sqrt(abs(1.0 / (0.5*(YC+ZC))) * (((0.5*(YC+ZC) / (2.0 * S23))**2 - 1.0) * (SIYY + SIZZ)) + ((SIYY + SIZZ) / (2.0 * S23))**2 + (SIYZ**2 - SIYY*SIZZ)/((S23)**2) + (SIXY**2 + SIXZ**2)/((0.5 * (S12+S13))**2))

Solid post processing field outputs
UT01_ELGA field
Available as results in the solid post processing file (UNIT = 84), in result UT01_XX.
Components:

X1 = S11 = stress along material dir 1 (= fibers usually)
X2 = S22 = stress along mat. Dir 2 (= transverse in plane usually)
X3 = S33 = stress along mat Dir 3 (=normal)
X4 = S12 = longitudinal shear stress Sigma_12 (in plane shear stress)
X5 = S13 = normal shear stress Sigma_13 (in transverse shear stress)
X6 = S23 = tranverse normal shear stress Sigma_23
X7= linearized matrix tensile FT criterion
X8= linearized matrix tensile FC criterion
X9= linearized matrix tensile MT criterion
X10= linearized matrix tensile MC criterion

Other outputs include stress state in global coordinate system as well as stress invariants and Tresca / Von Mises equivalent stress.

Summary of input / output files for Composite Designer simulation:

To perform a composite designer study, you will need to declare / map the following file names ⇔ Unit numbers in AsterStudy:

Model / initial solution stage: '

- Unit 20: input , either the Salome Mesh object or an external mesh in MED format

- Unit 80: output, global solution output, specify a output med file name ie "GlobalRes.med", contains the displacement fields and other global outputs if requested.
- Unit 81: output, model "concepts" output, specify a output ".med" file name i.e "Concepts.med", contains the shell thickness, local coord systems, material assignment.

Post processing stage

- Unit 2: output, layer by layer failure criteria & local stresses (shells), specify output med file name ie "FailPly.med"
- Unit 4: output, global failure criteria (max across layers, shells), specify output med file name ie "FailMax.med"
- Unit 84: output, solid regions failure criteria & local stresses, specify output med file name ie "Fail3D.med"

When loading the model definition command file as a graphical stage, you will see that the Datafiles for Unit 20, 80 and 81 are missing. In the Data File tab in Case View, simply right-click -> edit each entry.

To add a Unit to File mapping in the post processing , use the Data File tab in “Case View”, select the post-Processing stage and press the “Add file (+)” button to add a mapping

Composite Failure models: reference documents / information

Z. Hashin, 1980, Failure Criteria for Unidirectional Fiber Composites, Journal of Applied Mechanics

The quadratic failure criteria derived are now summarized:

Tensile Fiber Mode $\sigma_{11} > 0$

$$\left(\frac{\sigma_{11}}{\sigma_A^+}\right)^2 + \frac{1}{\tau_A^2}(\sigma_{12}^2 + \sigma_{13}^2) = 1 \qquad (10)$$

or

$$\sigma_{11} = \sigma_A^+ \qquad (11)$$

Compressive Fiber Mode $\sigma_{11} < 0$

$$\sigma_{11} = -\sigma_A^- \qquad (12)$$

Tensile Matrix Mode $\sigma_{22} + \sigma_{33} > 0$

$$\frac{1}{\sigma_T^{+2}}(\sigma_{22} + \sigma_{33})^2 + \frac{1}{\tau_T^2}(\sigma_{23}^2 - \sigma_{22}\sigma_{33}) + \frac{1}{\tau_A^2}(\sigma_{12}^2 + \sigma_{13}^2) = 1 \qquad (16)$$

Compressive Matrix Mode $\sigma_{22} + \sigma_{33} < 0$

$$\frac{1}{\sigma_T^-}\left[\left(\frac{\sigma_T^-}{2\tau_T}\right)^2 - 1\right](\sigma_{22} + \sigma_{33}) + \frac{1}{4\tau_T^2}(\sigma_{22} + \sigma_{33})^2 + \frac{1}{\tau_T^2}(\sigma_{23}^2 - \sigma_{22}\sigma_{33}) + \frac{1}{\tau_A^2}(\sigma_{12}^2 + \sigma_{13}^2) = 1 \qquad (19)$$

An efficient approach for predicting low-velocity impact force and damage in composite laminates

April 2015 · Composite Structures 130
DOI: 10.1016/j.compstruct.2015.04.023
Project: Predicitng low velocity impact damage in carbon fibre composites

J.k Zhang · Xiang Zhang

Failure Mode	Failure criterion	Material property degradation rule
Matrix tension cracking	$\left(\frac{\sigma_{yy}}{Y_T}\right)^2 + \left(\frac{\tau_{xy}}{S_{xy}}\right)^2 + \left(\frac{\tau_{yz}}{S_{yz}}\right)^2 \geq 1$	$E_{yy,d} = 0.2E_{yy}$ $G_{xy,d} = 0.2G_{xy}$ $G_{yz,d} = 0.2G_{yz}$
Matrix compression cracking	$\left(\frac{\sigma_{yy}}{Y_C}\right)^2 + \left(\frac{\tau_{xy}}{S_{xy}}\right)^2 + \left(\frac{\tau_{yz}}{S_{yz}}\right)^2 \geq 1$	$E_{yy,d} = 0.4E_{yy}$ $G_{xy,d} = 0.4G_{xy}$ $G_{yz,d} = 0.4G_{yz}$
Fibre tension failure	$\left(\frac{\sigma_{xx}}{X_T}\right)^2 + \left(\frac{\tau_{xy}}{S_{xy}}\right)^2 + \left(\frac{\tau_{yz}}{S_{yz}}\right)^2 \geq 1$	$E_{xx,d} = 0.07E_{xx}$
Fibre compression failure	$\left(\frac{\sigma_{xx}}{X_C}\right)^2 \geq 1$	$E_{xx,d} = 0.14E_{xx}$
Fibre-matrix shear-out	$\left(\frac{\sigma_{xx}}{X_C}\right)^2 + \left(\frac{\sigma_{xy}}{S_{xy}}\right)^2 + \left(\frac{\sigma_{yz}}{S_{yz}}\right)^2 \geq 1$	$G_{xy,d} = \upsilon_{xy,d} = 0$

Figure

Caption

Table 2 In-plane 3D Hashin-type failure criteria and material property degradation rules [31]

Progressive Failure Analysis of Laminated Composite Plates With Two Serial Pinned Joints

October 2015 · Mechanics of Advanced Materials and Structures 22(10) · Follow journal
DOI: 10.1080/15376494.2012.761302

Kadir Turan · Mete Onur Kaman · Mustafa Gur

Failure type	Failure condition	Failure criteria equation	Cell fill
Non-failure	—	—	
Fiber tensile failure	$\sigma_1 > 0$	$\left(\frac{\sigma_1}{X_t}\right)^2 + \left(\frac{\tau_{12}}{S}\right)^2 + \left(\frac{\tau_{13}}{S}\right)^2 \geq 1$	
Fiber compression failure	$\sigma_1 < 0$	$\left(\frac{\sigma_1}{X_c}\right)^2 \geq 1$	
Matrix tensile failure	$\sigma_2 > 0$	$\left(\frac{\sigma_2}{Y_t}\right)^2 + \left(\frac{\tau_{12}}{S}\right)^2 + \left(\frac{\tau_{23}}{S}\right)^2 \geq 1$	
Matrix compression failure	$\sigma_2 < 0$	$\left(\frac{\sigma_2}{Y_c}\right)^2 + \left(\frac{\tau_{12}}{S}\right)^2 + \left(\frac{\tau_{23}}{S}\right)^2 \geq 1$	
Fiber-matrix shear failure	$\sigma_1 < 0$	$\left(\frac{\sigma_1}{X_c}\right)^2 + \left(\frac{\tau_{12}}{S}\right)^2 + \left(\frac{\tau_{13}}{S}\right)^2 \geq 1$	

Caption

Table 2 . Three-dimensional Hashin Failure Criteria and colors that are seen in ANSYS [7, 8, 23]

3D fiber failure model generalized Hashin-Puck model in 3D, « UNIFIBER.FOR » model, Abaqus :

2.2. ***Hashin*** *and Puck failure criteria*

The damage variables associated with fiber/matrix failure in tension/compression are set to one instantaneously when the corresponding failure criterion is reached. We use the following generalization of Hashin's quadratic failure criteria (**Hashin**, 1980) and Puck's action plar model (Puck, 1998):

Tensile fiber mode: $s_{11} > 0$:

$$If \left(\frac{\sigma_{11}}{X_{1t}}\right)^2 + \left(\frac{\sigma_{12}}{S_{12}}\right)^2 + \left(\frac{\sigma_{13}}{S_{13}}\right)^2 = 1, d_{ft} = 1 \tag{5}$$

Compressive fiber mode: $s_{11} < 0$

$$If \frac{|\sigma_{11}|}{X_{1c}} = 1, d_{fc} = 1 \tag{6}$$

Tensile and Compressive matrix mode:

$$\begin{gathered} If \left[\left(\frac{\sigma_{11}}{2X_{1t}}\right)^2 + \frac{\sigma_{22}^2}{|X_{2t} \cdot X_{2c}|} + \left(\frac{\sigma_{12}}{S_{12}}\right)^2\right] + \sigma_{22}\left(\frac{1}{X_{2t}} + \frac{1}{X_{2c}}\right) = 1, and: \\ \sigma_{22} + \sigma_{33} > 0 \text{ then } d_{mt} = 1 \\ \sigma_{22} + \sigma_{33} < 0 \text{ then } d_{mc} = 1 \end{gathered} \tag{7}$$

The following material constants have been introduced in the previous equations:

X_{1t} = tensile failure stress in fiber direction

X_{1c} = compressive failure stress in fiber direction

X_{2t} = tensile failure stress in direction 2 (transverse to fiber direction)

X_{2c} = compressive failure stress in direction 2 (transverse to fiber direction)

X_{3t} = tensile failure stress in direction 3 (transverse to fiber direction)

X_{3c} = compressive failure stress in direction 3 (transverse to fiber direction)

S_{12} = failure shear stress in 1-2 plane

S_{13} = failure shear stress in 1-3 plane

S_{23} = failure shear stress in 2-3 plane

2.3. Criterion for element deletion

The element is deleted when the fibers fail in tension, d_{ft} = 1. The element is also deleted if the maximum principal nominal strain exceeds 1.0 or if the minimum principal nominal strain is lower than -0.8.

2.3. Stiffness proportional damping

Optionally, stiffness proportional damping can be specified. This generates viscous stresses in the form

$$\boldsymbol{\sigma}^{\nu} = \beta\, \mathbf{C} \cdot \dot{\boldsymbol{\varepsilon}} \tag{8}$$

Here b is the damping factor (units of time), $\mathbf{C}$ is the damaged elastic stiffness, and $\dot{\boldsymbol{\varepsilon}}$ is the strain rate.

ANSYS

5.4.4.4. Hashin Failure Criterion

In the Hashin criterion, criticality of tensile loads in the fiber direction is predicted with the expression

$$2\text{D}: f_f = \left(\frac{\sigma_1}{X_t}\right)^2 + \left(\frac{\tau_{12}}{S}\right)^2, \qquad \sigma_1 \geq 0 \tag{5.71}$$

$$3\text{D}: f_f = \left(\frac{\sigma_1}{X_t}\right)^2 + \left(\frac{\tau_{12}}{S}\right)^2 + \left(\frac{\tau_{13}}{R}\right)^2, \qquad \sigma_1 \geq 0 \tag{5.72}$$

Under compressive loads in the fiber direction, failure is predicted with an independent stress condition

$$f_f = -\frac{\sigma_1}{X_c}, \qquad \sigma_1 < 0 \tag{5.73}$$

In the case of tensile transverse stress, the expression for predicting matrix failure is

$$2\text{D}: f_m = \left(\frac{\sigma_2}{Y_t}\right)^2 + \left(\frac{\tau_{12}}{S}\right)^2 +, \qquad \sigma_2 \geq 0 \tag{5.74}$$

$$3\text{D}: f_m = \left(\frac{\sigma_2}{Y_t}\right)^2 + \left(\frac{\tau_{23}}{Q}\right)^2 + \left(\frac{\tau_{12}}{S}\right)^2 + \left(\frac{\tau_{13}}{R}\right)^2, \quad \sigma_2 \geq 0 \tag{5.75}$$

A more complex expression is used when the transverse stress is compressive:

$$2\text{D}: f_m = \left(\frac{\sigma_2}{2S}\right)^2 + \left(\frac{\tau_{12}}{S}\right)^2 + \left[\left(\frac{Y_c}{2S}\right)^2 - 1\right]\frac{\sigma_2}{Y_c}, \quad \sigma_2 < 0 \tag{5.76}$$

$$3\text{D}: f_m = \left(\frac{\sigma_2}{2Q}\right)^2 + \left(\frac{\tau_{23}}{Q}\right)^2 + \frac{\tau_{12}^2}{S^2} + \left[\left(\frac{Y_c}{2Q}\right)^2 - 1\right]\frac{\sigma_2}{Y_c}, \sigma_2 < 0 \tag{5.77}$$

Delamination (tension and compression) is predicted with this expression:

$$3\text{D}: f_d = \left(\frac{\sigma_3}{Z}\right)^2 + \left(\frac{\tau_{13}}{R}\right)^2 + \left(\frac{\tau_{23}}{Q}\right)^2 \tag{5.78}$$

https://forum.ansys.com/discussion/14070/hashin-failure-results

2.4.3.4. Physical Failure Criteria

The physical failure criteria are specially formulated to account for different damage mechanisms (fiber and matrix failure) in fiber-reinforced composite materials.

Predefined physical failure criteria include the following:

2.4.3.4.1. Hashin Fiber Failure Criterion

$$\xi_4 = \begin{cases} \left(\frac{\sigma_x}{\sigma^f_{xt}}\right)^2 + \frac{\sigma_{xy}{}^2 + \sigma_{xz}{}^2}{\left(\sigma^f_{xy}\right)^2} & if\ \sigma_x > 0 \\ \left(\frac{\sigma_x}{\sigma^f_{xc}}\right)^2 & if\ \sigma_x \leq 0 \end{cases} \tag{2–95}$$

2.4.3.4.2. Hashin Matrix Failure Criterion

$$\xi_5 = \begin{cases} \left(\frac{\sigma_y + \sigma_z}{\sigma^f_{yt}}\right)^2 + \frac{\sigma_{yz}{}^2 - \sigma_y\sigma_z}{\left(\sigma^f_{yz}\right)^2} + \frac{\sigma_{xy}{}^2 + \sigma_{xz}{}^2}{\left(\sigma^f_{xy}\right)^2} & if\ \sigma_y + \sigma_z > 0 \\ \frac{1}{\sigma^f_{yc}}\left(\left(\frac{\sigma^f_{yc}}{2\sigma^f_{yz}}\right)^2 - 1\right)\left(\sigma_y + \sigma_z\right) + \left(\frac{\sigma_y + \sigma_z}{2\sigma^f_{yz}}\right)^2 + \frac{\sigma_{yz}{}^2 - \sigma_y\sigma_z}{\left(\sigma^f_{yz}\right)^2} + \frac{\sigma_{xy}{}^2 + \sigma_{xz}{}^2}{\left(\sigma^f_{xy}\right)^2} & if\ \sigma_y + \sigma_z \leq 0 \end{cases} \tag{2–96}$$

ix is defined as:

$$[D]_d = \begin{bmatrix} \frac{C_{11}}{(1-d_f)} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{21} & \frac{C_{22}}{(1-d_m)} & C_{23} & 0 & 0 & 0 \\ C_{31} & C_{32} & \frac{C_{33}}{(1-d_m)} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{C_{44}}{(1-d_s)} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{C_{55}}{(1-d_s)} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{C_{66}}{(1-d_s)} \end{bmatrix}^{-1}$$

where:

$[C]$= compliance matrix of the undamaged material

d_f, d_m, d_s= fiber, matrix, and shear damage variables

Valid values are between 0 and 1, where 0 = no damage and 1 = complete loss of stiffness in the affected mode

FAIL	MAX	Maximum of all active failure criteria defined at the current location. (See **FCTYP**.) [2][6]
	EMAX	Maximum Strain Failure Criterion. [2][6]
	SMAX	Maximum Stress Failure Criterion. [2][6]
	TWSI	Tsai-Wu Strength Index Failure Criterion. [2][6]
	TWSR	Inverse of Tsai-Wu Strength Ratio Index Failure Criterion. [2][6]
	HFIB	Hashin Fiber Failure Criterion. [2][6][8]
	HMAT	Hashin Matrix Failure Criterion. [2][6][8]
	PFIB	Puck Fiber Failure Criterion. [2][6][8]
	PMAT	Puck Matrix Failure Criterion. [2][6][8]
	L3FB	LaRc03 Fiber Failure Criterion. [2][6][8]
	L3MT	LaRc03 Matrix Failure Criterion. [2][6][8]
	L4FB	LaRc04 Fiber Failure Criterion. [2][6][8]
	L4MT	LaRc04 Matrix Failure Criterion. [2][6][8]
	USR1, USR2, ..., USR9	User-defined failure criteria. [2][6][7][8]

https://ansyshelp.ansys.com/account/secured?returnurl=/Views/Secured/corp/v201/en/ans_thry/thy_str4.html?q=hashin%20theory

HASHIN CRITERIA , source ABAQUS :

Products: Abaqus/Standard Abaqus/Explicit Abaqus/CAE

Damage Initiation

Damage initiation refers to the onset of degradation at a material point. In Abaqus the damage initiation criteria for fibe initiation mechanisms: fiber tension, fiber compression, matrix tension, and matrix compression.

The initiation criteria have the following general forms:

Fiber tension $(\hat{\sigma}_{11} \geq 0)$:

$$F_f^t = \left(\frac{\hat{\sigma}_{11}}{X^T}\right)^2 + \alpha\left(\frac{\hat{\tau}_{12}}{S^L}\right)^2.$$

Fiber compression $(\hat{\sigma}_{11} < 0)$:

$$F_f^c = \left(\frac{\hat{\sigma}_{11}}{X^C}\right)^2.$$

Matrix tension $(\hat{\sigma}_{22} \geq 0)$:

$$F_m^t = \left(\frac{\hat{\sigma}_{22}}{Y^T}\right)^2 + \left(\frac{\hat{\tau}_{12}}{S^L}\right)^2.$$

Matrix compression $(\widehat{\sigma_{22}} < 0)$:

$$F_m^c = \left(\frac{\hat{\sigma}_{22}}{2S^T}\right)^2 + \left[\left(\frac{Y^C}{2S^T}\right)^2 - 1\right]\frac{\hat{\sigma}_{22}}{Y^C} + \left(\frac{\hat{\tau}_{12}}{S^L}\right)^2.$$

In the above equations

X^T
denotes the longitudinal tensile strength;

X^C
denotes the longitudinal compressive strength;

Y^T
denotes the transverse tensile strength;

Y^C
denotes the transverse compressive strength;

S^L
denotes the longitudinal shear strength;

S^T
denotes the transverse shear strength;

α
is a coefficient that determines the contribution of the shear stress to the fiber tensile initiation criterion; and

is a coefficient that determines the contribution of the shear stress to the fiber tensile initiation criterion; and

$\hat{\sigma}_{11}, \hat{\sigma}_{22}, \hat{\tau}_{12}$

are components of the effective stress tensor, $\hat{\sigma}$, that is used to evaluate the initiation criteria and which is computed from:

$$\hat{\sigma} = \mathbf{M}\sigma,$$

where σ is the true stress and $\mathbf{M}$ is the damage operator:

$$\mathbf{M} = \begin{bmatrix} \frac{1}{(1-d_f)} & 0 & 0 \\ 0 & \frac{1}{(1-d_m)} & 0 \\ 0 & 0 & \frac{1}{(1-d_s)} \end{bmatrix}.$$

d_f, d_m, and d_s are internal (damage) variables that characterize fiber, matrix, and shear damage, which are derived from damage variables d_f^t, d_f^c, d_m^t, and d_m^c, corresponding to the four modes previously discussed, as follows:

$$d_f = \begin{cases} d_f^t \text{ if } & \hat{\sigma}_{11} \geq 0, \\ d_f^c \text{ if } & \hat{\sigma}_{11} < 0, \end{cases}$$
$$d_m = \begin{cases} d_m^t \text{ if } & \hat{\sigma}_{22} \geq 0, \\ d_m^c \text{ if } & \hat{\sigma}_{22} < 0, \end{cases}$$
$$d_s = 1 - \left(1 - d_f^t\right)\left(1 - d_f^c\right)\left(1 - d_m^t\right)\left(1 - d_m^c\right).$$

Prior to any damage initiation and evolution the damage operator, $\mathbf{M}$, is equal to the identity matrix, so $\hat{\sigma} = \sigma$. Once damage initiation and evolution has occurred for at least one mode, the damage operator becomes significant in the criteria for damage initiation of other modes (see Damage evolution and element removal for fiber-reinforced composites for discussion of damage evolution). The effective stress, $\hat{\sigma}$, is intended to represent the stress acting over the damaged area that effectively resists the internal forces.

The initiation criteria presented above can be specialized to obtain the model proposed in Hashin and Rotem (1973) by setting $\alpha = 0.0$ and $S^T = Y^C/2$ or the model proposed in Hashin (1980) by setting $\alpha = 1.0$.

An output variable is associated with each initiation criterion (fiber tension, fiber compression, matrix tension, matrix compression) to indicate whether the criterion has been met. A value of 1.0 or higher indicates that the initiation criterion has been met (see Output for further details). If you define a damage initiation model without defining an associated evolution law, the initiation criteria will affect only output. Thus, you can use these criteria to evaluate the propensity of the material to undergo damage without modeling the damage process.

3D fiber failure model generalized Hashin-Puck model in 3D, « UNIFIBER.FOR » model, Abaqus :

*2.2. **Hashin** and Puck failure criteria*

The damage variables associated with fiber/matrix failure in tension/compression are set to one instantaneously when the corresponding failure criterion is reached. We use the following generalization of Hashin's quadratic failure criteria (**Hashin**, 1980) and Puck's action plar model (Puck, 1998):

Tensile fiber mode: $s_{11} > 0$:

$$If \left(\frac{\sigma_{11}}{X_{1t}}\right)^2 + \left(\frac{\sigma_{12}}{S_{12}}\right)^2 + \left(\frac{\sigma_{13}}{S_{13}}\right)^2 = 1, d_{ft} = 1 \tag{5}$$

Compressive fiber mode: $s_{11} < 0$

$$If \frac{|\sigma_{11}|}{X_{1c}} = 1, d_{fc} = 1 \tag{6}$$

Tensile and Compressive matrix mode:

$$\begin{gathered} If \left[\left(\frac{\sigma_{11}}{2X_{1t}}\right)^2 + \frac{\sigma_{22}^2}{|X_{2t} \cdot X_{2c}|} + \left(\frac{\sigma_{12}}{S_{12}}\right)^2\right] + \sigma_{22}\left(\frac{1}{X_{2t}} + \frac{1}{X_{2c}}\right) = 1, and: \\ \sigma_{22} + \sigma_{33} > 0 \; then \; d_{mt} = 1 \\ \sigma_{22} + \sigma_{33} < 0 \; then \; d_{mc} = 1 \end{gathered} \tag{7}$$

The following material constants have been introduced in the previous equations:

X_{1t} = tensile failure stress in fiber direction

X_{1c} = compressive failure stress in fiber direction

X_{2t} = tensile failure stress in direction 2 (transverse to fiber direction)

X_{2c} = compressive failure stress in direction 2 (transverse to fiber direction)

X_{3t} = tensile failure stress in direction 3 (transverse to fiber direction)

X_{3c} = compressive failure stress in direction 3 (transverse to fiber direction)

S_{12} = failure shear stress in 1-2 plane

S_{13} = failure shear stress in 1-3 plane

S_{23} = failure shear stress in 2-3 plane

2.3. Criterion for element deletion

The element is deleted when the fibers fail in tension, d_{ft} = 1. The element is also deleted if the maximum principal nominal strain exceeds 1.0 or if the minimum principal nominal strain is lower than -0.8.

2.3. Stiffness proportional damping

Optionally, stiffness proportional damping can be specified. This generates viscous stresses in the form

$$\boldsymbol{\sigma}^{v} = \beta\, \mathbf{C} \cdot \dot{\boldsymbol{\varepsilon}} \tag{8}$$

Here b is the damping factor (units of time), $\mathbf{C}$ is the damaged elastic stiffness, and $\dot{\boldsymbol{\varepsilon}}$ is the strain rate.

Next Development steps

TODO:

1. Validate post pro for solids including stress state transformation matrices
2. Prepare reference validation cases and documentation
3. Implement simple load case / support definitions in GUI
4. Add interlaminar shear output (rotation similar to S11 and S22 but for S13 and S23)