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Abaqus/Explicit VUMAT for the simulation of damage and failure in unidirectional fiber composite materials

Question

Abaqus/Explicit VUMAT for the simulation of damage and failure in unidirectional fiber composite materials

Answer

(The following applies to any Abaqus release.)

1. Introduction

This Answer describes a constitutive model for unidirectional fiber reinforced composites for use in Abaqus/Explicit. The constitutive model for the fiber is based on Hashin's failure criteria for unidirectional fiber composites (Hashin, 1980). For the matrix material, a constitutive model based on Puck's action plane theory (Puck, 1998) is used. Other well-known failure criteria can be incorporated with simple modifications to the existing code. The model has been implemented as a VUMAT user subroutine and is attached below. It is intended for use with three-dimensional stress-displacement continuum elements (C3D4, C3D6, C3D8R, C3D10M).

Note that Versions 6.7 and higher of Abaqus contain native functionality for modeling the initiation and evolution of damage in composite materials for elements using a plane stress formulation.

2. Continuum damage model unidirectional fiber composites

2.1. Elastic stress-strain relations

It is assumed that the elastic stress-strain relations are given by orthotropic damaged elasticity. Referred to a local coordinate system ($OX_1X_2X_3$) with the OX_1 axis aligned with the fiber directions, and the OX_3 axis normal to the plane of the lamina, the elastic relations take the form:

$$\begin{pmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{12} \\ \sigma_{23} \\ \sigma_{31} \end{pmatrix} = \begin{pmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{13} & C_{23} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & 2G_{12} & 0 & 0 \\ 0 & 0 & 0 & 0 & 2G_{23} & 0 \\ 0 & 0 & 0 & 0 & 0 & 2G_{31} \end{pmatrix} \begin{pmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ \varepsilon_{12} \\ \varepsilon_{23} \\ \varepsilon_{31} \end{pmatrix} \tag{1}$$

The following damage variables are introduced: d_{ft} and d_{fc}, associated with fiber tension and compression failure modes respectively; and d_{mt} and d_{mc}, associated with the corresponding failure modes in the matrix. Global fiber and matrix damage variables are also defined as:

$$\begin{aligned} d_f &= 1-(1-d_{ft})(1-d_{fc}) \\ d_m &= 1-(1-d_{mt})(1-d_{mc}) \end{aligned} \tag{2}$$

The damaged elastic constants, C_{ij}, are computed in terms of the initial elastic constants, C_{ij}^0, and the damage variables according to:

$$
\begin{aligned}
C_{11} &= (1-d_f)C_{11}^0 \\
C_{22} &= (1-d_f)(1-d_m)C_{22}^0 \\
C_{33} &= (1-d_f)(1-d_m)C_{33}^0 \\
C_{12} &= (1-d_f)(1-d_m)C_{12}^0 \\
C_{23} &= (1-d_f)(1-d_m)C_{23}^0 \\
C_{13} &= (1-d_f)(1-d_m)C_{13}^0 \\
G_{12} &= (1-d_f)(1-s_{mt}d_{mt})(1-s_{mc}d_{mc})G_{12}^0 \\
G_{23} &= (1-d_f)(1-s_{mt}d_{mt})(1-s_{mc}d_{mc})G_{23}^0 \\
G_{31} &= (1-d_f)(1-s_{mt}d_{mt})(1-s_{mc}d_{mc})G_{31}^0
\end{aligned} \tag{3}
$$

The factors s_{mt} and s_{mc} in the definitions of the shear moduli are introduced to control the loss of shear stiffness caused by matrix tensile and compressive failure respectively. The following values were assumed: s_{mt} = 0.9 and s_{mc}= 0.5.

The following expressions are used to compute the initial (undamaged) elastic constants from the values of Young's modulus and Poisson's ratio:

$$
\begin{aligned}
C_{11}^0 &= E_{11}^0(1-\nu_{23}\nu_{32})\Gamma \\
C_{22}^0 &= E_{22}^0(1-\nu_{13}\nu_{31})\Gamma \\
C_{33}^0 &= E_{33}^0(1-\nu_{12}\nu_{21})\Gamma \\
C_{12}^0 &= E_{11}^0(\nu_{21}+\nu_{31}\nu_{23})\Gamma \\
C_{23}^0 &= E_{22}^0(\nu_{32}+\nu_{12}\nu_{31})\Gamma \\
C_{13}^0 &= E_{11}^0(\nu_{31}+\nu_{21}\nu_{32})\Gamma \\
\Gamma &= 1/(1-\nu_{12}\nu_{21}-\nu_{23}\nu_{32}-\nu_{31}\nu_{13}-2\nu_{21}\nu_{32}\nu_{13})
\end{aligned} \tag{4}
$$

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 plane model (Puck, 1998):

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

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

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

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

Tensile and Compressive matrix mode:

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

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

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

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

3. User interface

A synopsis of the interface is shown below. The number of solution dependent variables (under `*DEPVAR`) is 17, and the `DELETE` parameter is equal to 5. Refer to Table 1 for a detailed description of each material constant specified in the keyword interface.

```
*MATERIAL, NAME= matName
*DENSITY
```

ρ

```
*USER MATERIAL, CONSTANTS=32
** Line 1:
```

$E_{11}^0, E_{22}^0, E_{33}^0, \nu_{12}, \nu_{13}, \nu_{23}, G_{12}^0, G_{13}^0$

```
** Line 2:
```

G_{23}^0, β

```
** Line 3:
```

$X_{1t}, X_{1c}, X_{2t}, X_{2c}, X_{3t}, X_{3c}$

```
** Line 4:
```

S_{12}, S_{13}, S_{23}

```
*DEPVAR, DELETE=5
 17
```

LINE: 1

Pos.	Symbol	Description
1	E_{11}^0	Young's modulus along fiber direction 1
2	E_{22}^0	Young's modulus along matrix direction 2
3	E_{33}^0	Young's modulus along matrix direction 3
4	ν_{12}	Poisson's ratio
5	ν_{13}	Poisson's ratio
6	ν_{23}	Poisson's ratio
7	G_{12}^0	Shear modulus in 1-2 plane
8	G_{13}^0	Shear modulus in 1-3 plane

LINE: 2

Pos.	Symbol	Description
1	G_{23}^{0}	Shear modulus in 2-3 plane
2	β	Coefficient for stiffness proportional damping
6-8		*Not used*

LINE: 3

Pos.	Symbol	Description
1	X_{1t}	Tensile failure stress in fiber direction (direction 1)
2	X_{1c}	Compressive failure stress in fiber direction (direction 1)
3	X_{2t}	Tensile failure stress in direction 2 (transverse to fiber direction)
4	X_{2c}	Compressive failure stress in direction 2 (transverse to fiber direction)
5	X_{3t}	Tensile failure stress in direction 3 (transverse to fiber direction)
6	X_{3c}	Compressive failure stress in direction 3 (transverse to fiber direction)
7-8		*Not used*

LINE: 4

Pos.	Symbol	Description
1	S_{12}	Shear strength in 1-2 plane
2	S_{13}	Shear strength in 1-3 plane
3	S_{23}	Shear strength in 2-3 plane
4-8		*Not used*

***Table 1**. User material constants for the unidirectional fiber composite model.*

4. Output

In addition to the standard (material-independent) output variables in Abaqus/Explicit for stress-displacement elements (such as stress, `S`, strain, `LE`, element `STATUS`, etc.) the following output variables have a special meaning for the user material for unidirectional fiber composites:

Output Variable	Symbol	Description
`SDV1`	d_{ft}	Tensile damage along fiber direction 1
`SDV2`	d_{fc}	Compressive damage along fiber direction 1
`SDV3`	d_{mt}	Tensile damage along fiber direction 2
`SDV4`	d_{mc}	Compressive damage along fiber direction 2
`SDV5`	`MpStatus`	Material point status: 1 if active, 0 if failed.
`SDV6-11`	σ_{ij}^{v}	Components of viscous stresses if beta damping is active
`SDV12-17`	ε_{ij}^{el}	Components of elastic strain tensor

5. References

[1] Hashin, Z., “Failure Criteria for Unidirectional Fiber Composites,” *Journal of Applied Mechanics*, Vol. 47, 1980, pp. 329-334.

[2] Puck, A and Schürmann, H., “Failure Analysis of FRP Laminates By Means of Physically Based Phenomenological Models,” *Composites Science and Technology*, Vol. 58, 1998, pp. 1045-1067.

File Attachments

- uniFiber.for