mat. 59

Implementation of Three-Dimensional Composite Failure Model into DYNA3D

W. Cheng
Corporate Technology Center
FMC Corporateion

J. Hallquist
Livermore Software Technology, Inc.

ABSTRACT

The composite failure model simulates the 3-dimensional behavior of an orthotropic composite structure. It predicts the onset of four major failure modes, namely tensile failure, transverse shear failure, compressive failure and delamination. The occurrence of these failure modes is predicted by four independent failure criteria. It is believed that these failure mechanisms contribute to an ultimate failure of a composite system. Complete failure of the composites is facilitated by progressively degrading the properties of the composites.

The following provides an outline of the model:

A. Constitutive Behavior

The 3-D constitutive model is based on orthotropic material and is given below:

$$\begin{bmatrix} \frac{1}{E_a} & -\frac{\nu_{ab}}{E_b} & -\frac{\nu_{ac}}{E_c} & 0. & 0. & 0. \\ -\frac{\nu_{ba}}{E_a} & \frac{1}{E_b} & -\frac{\nu_{bc}}{E_c} & 0. & 0. & 0. \\ -\frac{\nu_{ca}}{E_a} & -\frac{\nu_{cb}}{E_b} & \frac{1}{E_c} & 0. & 0. & 0. \\ 0. & 0. & 0. & \frac{1}{G_{bc}} & 0. & 0. \\ 0. & 0. & 0. & 0. & \frac{1}{G_{ca}} & 0. \\ 0. & 0. & 0. & 0. & 0. & \frac{1}{G_{ab}} \end{bmatrix} \begin{Bmatrix} \sigma_{aa} \\ \sigma_{bb} \\ \sigma_{cc} \\ \sigma_{bc} \\ \sigma_{ca} \\ \sigma_{ab} \end{Bmatrix} = \begin{Bmatrix} \varepsilon_{aa} \\ \varepsilon_{bb} \\ \varepsilon_{cc} \\ \gamma_{bc} \\ \gamma_{ca} \\ \gamma_{ab} \end{Bmatrix}$$

28 Y_t Z_t 29

27 X_t X_c 33

30 S_{ab} Y_c 34

31 S_{ac} Z_c 35

32 S_{bc}

B. Failure Criteria

1. Tensile Failures

a. Longitudinal ($\sigma_{aa} > 0.$)

Longitudinal tensile failure occurs if the following is met:

$$\left(\frac{\sigma_{aa}}{X_t}\right)^2 + \left(\frac{\sigma_{ab}}{S_{ab}}\right)^2 + \left(\frac{\sigma_{ac}}{S_{ac}}\right)^2 \geq 1.$$

When failure occurs, the following must be set:

$$\begin{bmatrix} \frac{1}{E_a} & -\frac{\nu_{ab}}{E_b} & -\frac{\nu_{ac}}{E_c} & 0. & 0. & 0. \\ -\frac{\nu_{ba}}{E_a} & \frac{1}{E_b} & -\frac{\nu_{bc}}{E_c} & 0. & 0. & 0. \\ -\frac{\nu_{ca}}{E_a} & -\frac{\nu_{cb}}{E_b} & \frac{1}{E_c} & 0. & 0. & 0. \\ 0. & 0. & 0. & \frac{1}{G_{bc}} & 0. & 0. \\ 0. & 0. & 0. & 0. & \frac{1}{G_{ca}} & 0. \\ 0. & 0. & 0. & 0. & 0. & \frac{1}{G_{ab}} \end{bmatrix} \rightarrow \begin{bmatrix} 0. & 0. & 0. & 0. & 0. & 0. \\ 0. & \frac{1}{E_b} & 0. & 0. & 0. & 0. \\ 0. & 0. & \frac{1}{E_c} & 0. & 0. & 0. \\ 0. & 0. & 0. & 0. & 0. & 0. \\ 0. & 0. & 0. & 0. & 0. & 0. \\ 0. & 0. & 0. & 0. & 0. & 0. \end{bmatrix}$$

and

$$\begin{Bmatrix} \sigma_{aa} \\ \sigma_{bb} \\ \sigma_{cc} \\ \sigma_{bc} \\ \sigma_{ca} \\ \sigma_{ab} \end{Bmatrix} \rightarrow \begin{Bmatrix} 0. \\ \sigma_{bb} \\ \sigma_{cc} \\ 0. \\ 0. \\ 0. \end{Bmatrix}$$

Degradation is performed over a small period of time. Option is to be available for elimination of failed elements when transverse tensile failure criteria is also met. Another option is to be available for elimination of failed elements when a critical strain is reached.

B. Failure Criteria

1. Tensile Failures (Cont.)

b. Transverse ($\sigma_{bb} > 0.$)

Transverse tensile failure occurs if the following is met:

$$\left(\frac{\sigma_{bb}}{Y_t}\right)^2 + \left(\frac{\sigma_{ab}}{S_{ab}}\right)^2 + \left(\frac{\sigma_{bc}}{S_{bc}}\right)^2 \geq 1.$$

When failure occurs, the following must be set:

$$\begin{bmatrix} \frac{1}{E_a} & -\frac{\nu_{ab}}{E_b} & -\frac{\nu_{ac}}{E_c} & 0. & 0. & 0. \\ -\frac{\nu_{ba}}{E_a} & \frac{1}{E_b} & -\frac{\nu_{bc}}{E_c} & 0. & 0. & 0. \\ -\frac{\nu_{ca}}{E_a} & -\frac{\nu_{cb}}{E_b} & \frac{1}{E_c} & 0. & 0. & 0. \\ 0. & 0. & 0. & \frac{1}{G_{bc}} & 0. & 0. \\ 0. & 0. & 0. & 0. & \frac{1}{G_{ca}} & 0. \\ 0. & 0. & 0. & 0. & 0. & \frac{1}{G_{ab}} \end{bmatrix} \rightarrow \begin{bmatrix} \frac{1}{E_a} & 0. & 0. & 0. & 0. & 0. \\ 0. & 0. & 0. & 0. & 0. & 0. \\ 0. & 0. & \frac{1}{E_c} & 0. & 0. & 0. \\ 0. & 0. & 0. & 0. & 0. & 0. \\ 0. & 0. & 0. & 0. & 0. & 0. \\ 0. & 0. & 0. & 0. & 0. & 0. \end{bmatrix}$$

and

$$\begin{Bmatrix} \sigma_{aa} \\ \sigma_{bb} \\ \sigma_{cc} \\ \sigma_{bc} \\ \sigma_{ca} \\ \sigma_{ab} \end{Bmatrix} \rightarrow \begin{Bmatrix} \sigma_{aa} \\ 0. \\ \sigma_{cc} \\ 0. \\ 0. \\ 0. \end{Bmatrix}$$

Degradation is performed over a small period of time. Option is to be available for elimination of failed elements when longitudinal tensile failure criteria is also met. Another option is to be available for elimination of failed elements when a critical strain is reached.

B. Failure Criteria (Cont.)

2. Thru-Thickness Shear Failures

a. Longitudinal ($\sigma_{aa} > 0.$)

Longitudinal thru-thickness shear failure occurs if the following is met:

$$\left(\frac{\sigma_{aa}}{X_t}\right)^2 + \left(\frac{\sigma_{ac}}{S_{ac}}\right)^2 \geq 1.$$

where the first term is considered only if $\sigma_{aa} > 0$

When failure occurs, the following must be set:

$$\begin{bmatrix} \frac{1}{E_a} & -\frac{\nu_{ab}}{E_b} & -\frac{\nu_{ac}}{E_c} & 0. & 0. & 0. \\ -\frac{\nu_{ba}}{E_a} & \frac{1}{E_b} & -\frac{\nu_{bc}}{E_c} & 0. & 0. & 0. \\ -\frac{\nu_{ca}}{E_a} & -\frac{\nu_{cb}}{E_b} & \frac{1}{E_c} & 0. & 0. & 0. \\ 0. & 0. & 0. & \frac{1}{G_{bc}} & 0. & 0. \\ 0. & 0. & 0. & 0. & \frac{1}{G_{ca}} & 0. \\ 0. & 0. & 0. & 0. & 0. & \frac{1}{G_{ab}} \end{bmatrix} \rightarrow \begin{bmatrix} 0. & 0. & 0. & 0. & 0. & 0. \\ 0. & \frac{1}{E_b} & 0. & 0. & 0. & 0. \\ 0. & 0. & \frac{1}{E_c} & 0. & 0. & 0. \\ 0. & 0. & 0. & 0. & 0. & 0. \\ 0. & 0. & 0. & 0. & 0. & 0. \\ 0. & 0. & 0. & 0. & 0. & 0. \end{bmatrix}$$

and

$$\begin{Bmatrix} \sigma_{aa} \\ \sigma_{bb} \\ \sigma_{cc} \\ \sigma_{bc} \\ \sigma_{ca} \\ \sigma_{ab} \end{Bmatrix} \rightarrow \begin{Bmatrix} 0. \\ \sigma_{bb} \\ \sigma_{cc} \\ 0. \\ 0. \\ 0. \end{Bmatrix}$$

Degradation is performed over a small period of time. Option is to be available for elimination of failed elements when transverse thru-thickness failure criteria is also met. Another option is to be available for elimination of failed elements when a critical strain is reached.

B. Failure Criteria

2. Thru-Thickness Shear Failures (Cont.)

b. Transverse ($\sigma_{bb} > 0.$)

Transverse thru-thickness shear failure occurs if the following is met:

$$\left(\frac{\sigma_{bb}}{Y_t}\right)^2 + \left(\frac{\sigma_{bc}}{S_{bc}}\right)^2 \geq 1.$$

where the first term is considered only if $\sigma_{bb} > 0$

When failure occurs, the following must be set:

$$\begin{bmatrix} \frac{1}{E_a} & -\frac{\nu_{ab}}{E_b} & -\frac{\nu_{ac}}{E_c} & 0. & 0. & 0. \\ -\frac{\nu_{ba}}{E_a} & \frac{1}{E_b} & -\frac{\nu_{bc}}{E_c} & 0. & 0. & 0. \\ -\frac{\nu_{ca}}{E_a} & -\frac{\nu_{cb}}{E_b} & \frac{1}{E_c} & 0. & 0. & 0. \\ 0. & 0. & 0. & \frac{1}{G_{bc}} & 0. & 0. \\ 0. & 0. & 0. & 0. & \frac{1}{G_{ca}} & 0. \\ 0. & 0. & 0. & 0. & 0. & \frac{1}{G_{ab}} \end{bmatrix} \rightarrow \begin{bmatrix} \frac{1}{E_a} & 0. & 0. & 0. & 0. & 0. \\ 0. & 0. & 0. & 0. & 0. & 0. \\ 0. & 0. & \frac{1}{E_c} & 0. & 0. & 0. \\ 0. & 0. & 0. & 0. & 0. & 0. \\ 0. & 0. & 0. & 0. & 0. & 0. \\ 0. & 0. & 0. & 0. & 0. & 0. \end{bmatrix}$$

and

$$\begin{Bmatrix} \sigma_{aa} \\ \sigma_{bb} \\ \sigma_{cc} \\ \sigma_{bc} \\ \sigma_{ca} \\ \sigma_{ab} \end{Bmatrix} \rightarrow \begin{Bmatrix} \sigma_{aa} \\ 0. \\ \sigma_{cc} \\ 0. \\ 0. \\ 0. \end{Bmatrix}$$

Degradation is performed over a small period of time. Option is to be available for elimination of failed elements when longitudinal thru-thickness failure criteria is also met. Another option is to be available for elimination of failed elements when a critical strain is reached.

B. Failure Criteria (Cont.)

3. Delamination Failures

Delamination failure occurs if the following is met:

$$\left(\frac{\sigma_{cc}}{Z_t}\right)^2+\left(\frac{\sigma_{ac}}{S_{ac}}\right)^2+\left(\frac{\sigma_{bc}}{S_{bc}}\right)^2 \geq 1.$$

where the first term is considered only if $\sigma_{cc} > 0$

When failure occurs, the following must be set:

$$\begin{bmatrix} \frac{1}{E_a} & -\frac{\nu_{ab}}{E_b} & -\frac{\nu_{ac}}{E_c} & 0. & 0. & 0. \\ -\frac{\nu_{ba}}{E_a} & \frac{1}{E_b} & -\frac{\nu_{bc}}{E_c} & 0. & 0. & 0. \\ -\frac{\nu_{ca}}{E_a} & -\frac{\nu_{cb}}{E_b} & \frac{1}{E_c} & 0. & 0. & 0. \\ 0. & 0. & 0. & \frac{1}{G_{bc}} & 0. & 0. \\ 0. & 0. & 0. & 0. & \frac{1}{G_{ca}} & 0. \\ 0. & 0. & 0. & 0. & 0. & \frac{1}{G_{ab}} \end{bmatrix} \rightarrow \begin{bmatrix} \frac{1}{E_a} & 0. & 0. & 0. & 0. & 0. \\ 0. & \frac{1}{E_b} & 0. & 0. & 0. & 0. \\ 0. & 0. & 0. & 0. & 0. & 0. \\ 0. & 0. & 0. & 0. & 0. & 0. \\ 0. & 0. & 0. & 0. & 0. & 0. \\ 0. & 0. & 0. & 0. & 0. & 0. \end{bmatrix}$$

and

$$\begin{Bmatrix} \sigma_{aa} \\ \sigma_{bb} \\ \sigma_{cc} \\ \sigma_{bc} \\ \sigma_{ca} \\ \sigma_{ab} \end{Bmatrix} \rightarrow \begin{Bmatrix} \sigma_{aa} \\ \sigma_{bb} \\ 0. \\ 0. \\ 0. \\ 0. \end{Bmatrix}$$

Degradation is performed over a small period of time. No option is available for elimination of failed elements for this failure mechanism.

B. Failure Criteria (Cont.)

4. Compressive Failures

a. Longitudinal compressive failure occurs if the following is met:

$$\left(\frac{\sigma_{aa}}{X_c}\right)^2 \geq 1.$$

where $\sigma_{aa} < 0.$

$$\begin{bmatrix} \frac{1}{E_a} & -\frac{\nu_{ab}}{E_b} & -\frac{\nu_{ac}}{E_c} & 0. & 0. & 0. \\ -\frac{\nu_{ba}}{E_a} & \frac{1}{E_b} & -\frac{\nu_{bc}}{E_c} & 0. & 0. & 0. \\ -\frac{\nu_{ca}}{E_a} & -\frac{\nu_{cb}}{E_b} & \frac{1}{E_c} & 0. & 0. & 0. \\ 0. & 0. & 0. & \frac{1}{G_{bc}} & 0. & 0. \\ 0. & 0. & 0. & 0. & \frac{1}{G_{ca}} & 0. \\ 0. & 0. & 0. & 0. & 0. & \frac{1}{G_{ab}} \end{bmatrix} \rightarrow \begin{bmatrix} 0. & 0. & 0. & 0. & 0. & 0. \\ 0. & \frac{1}{E_b} & 0. & 0. & 0. & 0. \\ 0. & 0. & \frac{1}{E_c} & 0. & 0. & 0. \\ 0. & 0. & 0. & 0. & 0. & 0. \\ 0. & 0. & 0. & 0. & 0. & 0. \\ 0. & 0. & 0. & 0. & 0. & 0. \end{bmatrix}$$

and

$$\begin{Bmatrix} \sigma_{aa} \\ \sigma_{bb} \\ \sigma_{cc} \\ \sigma_{bc} \\ \sigma_{ca} \\ \sigma_{ab} \end{Bmatrix} \rightarrow \begin{Bmatrix} 0. \\ \sigma_{bb} \\ \sigma_{cc} \\ 0. \\ 0. \\ 0. \end{Bmatrix}$$

Degradation is performed over a small period of time. Option is to be available for elimination of failed elements when a critical strain is reached.

B. Failure Criteria

4. Compressive Failures (Cont.)

b. Transverse compressive failure occurs if the following is met:

$$\left(\frac{\sigma_{bb}}{S_{ab}+S_{bc}}\right)^2+\left[\left(\frac{Y_c}{S_{ab}+S_{bc}}\right)^2-1\right]\frac{\sigma_b}{|Y_c|}+\left(\frac{\sigma_{ab}}{S_{ab}}\right)^2+\left(\frac{\sigma_{bc}}{S_{bc}}\right)^2\geq 1.$$

where $\sigma_{bb} < 0$.

$$\begin{bmatrix} \frac{1}{E_a} & -\frac{\nu_{ab}}{E_b} & -\frac{\nu_{ac}}{E_c} & 0. & 0. & 0. \\ -\frac{\nu_{ba}}{E_a} & \frac{1}{E_b} & -\frac{\nu_{bc}}{E_c} & 0. & 0. & 0. \\ -\frac{\nu_{ca}}{E_a} & -\frac{\nu_{cb}}{E_b} & \frac{1}{E_c} & 0. & 0. & 0. \\ 0. & 0. & 0. & \frac{1}{G_{bc}} & 0. & 0. \\ 0. & 0. & 0. & 0. & \frac{1}{G_{ca}} & 0. \\ 0. & 0. & 0. & 0. & 0. & \frac{1}{G_{ab}} \end{bmatrix} \rightarrow \begin{bmatrix} \frac{1}{E_a} & 0. & 0. & 0. & 0. & 0. \\ 0. & 0. & 0. & 0. & 0. & 0. \\ 0. & 0. & \frac{1}{E_c} & 0. & 0. & 0. \\ 0. & 0. & 0. & 0. & 0. & 0. \\ 0. & 0. & 0. & 0. & 0. & 0. \\ 0. & 0. & 0. & 0. & 0. & 0. \end{bmatrix}$$

and

$$\begin{Bmatrix} \sigma_{aa} \\ \sigma_{bb} \\ \sigma_{cc} \\ \sigma_{bc} \\ \sigma_{ca} \\ \sigma_{ab} \end{Bmatrix} \rightarrow \begin{Bmatrix} \sigma_{aa} \\ 0. \\ \sigma_{cc} \\ 0. \\ 0. \\ 0. \end{Bmatrix}$$

Degradation is performed over a small period of time. Option is to be available for elimination of failed elements when a critical volumeric strain is reached.

B. Failure Criteria

4. Compressive Failures (Cont.)

c. Thru-thickness compressive failure occurs if the following is met:

$$\left(\frac{\sigma_{cc}}{S_{ac}+S_{bc}}\right)^2+\left[\left(\frac{Z_c}{S_{ac}+S_{bc}}\right)^2-1\right]\frac{\sigma_{cc}}{|Z_c|}+\left(\frac{\sigma_{ac}}{S_{ac}}\right)^2+\left(\frac{\sigma_{bc}}{S_{bc}}\right)^2\geq 1.$$

where the first term is considered only if $\sigma_{cc} < 0$.

When failure occurs, the following must be set:

$$\begin{bmatrix} \frac{1}{E_a} & -\frac{\nu_{ab}}{E_b} & -\frac{\nu_{ac}}{E_c} & 0. & 0. & 0. \\ -\frac{\nu_{ba}}{E_a} & \frac{1}{E_b} & -\frac{\nu_{bc}}{E_c} & 0. & 0. & 0. \\ -\frac{\nu_{ca}}{E_a} & -\frac{\nu_{cb}}{E_b} & \frac{1}{E_c} & 0. & 0. & 0. \\ 0. & 0. & 0. & \frac{1}{G_{bc}} & 0. & 0. \\ 0. & 0. & 0. & 0. & \frac{1}{G_{ca}} & 0. \\ 0. & 0. & 0. & 0. & 0. & \frac{1}{G_{ab}} \end{bmatrix} \rightarrow \begin{bmatrix} \frac{1}{E_a} & 0. & 0. & 0. & 0. & 0. \\ 0. & \frac{1}{E_b} & 0. & 0. & 0. & 0. \\ 0. & 0. & 0. & 0. & 0. & 0. \\ 0. & 0. & 0. & 0. & 0. & 0. \\ 0. & 0. & 0. & 0. & 0. & 0. \\ 0. & 0. & 0. & 0. & 0. & 0. \end{bmatrix}$$

and

$$\begin{Bmatrix} \sigma_{aa} \\ \sigma_{bb} \\ \sigma_{cc} \\ \sigma_{bc} \\ \sigma_{ca} \\ \sigma_{ab} \end{Bmatrix} \rightarrow \begin{Bmatrix} \sigma_{aa} \\ \sigma_{bb} \\ 0. \\ 0. \\ 0. \\ 0. \end{Bmatrix}$$

Degradation is performed over a small period of time. No option is available for elimination of failed elements when a critical volumeric strain is reached.

C. Strain-rate Dependency

Option is to be provided to define strain-rate dependent failure strengths.