

**USER'S MANUAL FOR LS-DYNA MAT162
UNIDIRECTIONAL AND PLAIN WEAVE COMPOSITE
PROGRESSIVE FAILURE MODELS**

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This model may be used to simulate progressive failure in composite materials consisting of unidirectional and woven fabric layers subjected to high strain-rate and high pressure loading conditions. The model is a generalization of the layer failure model reported in [1]. The MLT damage mechanics approach [2] has been adopted to characterize the softening behavior after damage initiation.

Card Format

Card 1 1 2 3 4 5 6 7 8

Variable	MID	RO	EA	EB	EC	PRBA	PRCA	PRCB
Type	I	F	F	F	F	F	F	F

Card 2

Variable	GAB	GBC	GCA	AOPT				
Type	F	F	F	F				

Card 3

Variable	XP	YP	ZP	A1	A2	A3		
Type	F	F	F	F	F	F		

Card 4

Variable	V1	V2	V3	D1	D2	D3	BETA	
Type	F	F	F	F	F	F	F	

Card 5

Variable	SAT	SAC	SBT	SBC	SCT	SFC	SFS	SAB
Type	F	F	F	F	F	F	F	F

Card 6

Variable	SBC	SCA	SFFC	AMODEL	E_LIMT	PHIC	S_DELM	
Type	F	F	F	F	F	F	F	

Card 7

Variable	OMGMX	ECRSH	EEXPN	CR1	AM1			
Type	F	F	F	F	F			

Card 8

Variable	AM2	AM3	AM4	CR2	CR3	CR4		
Type	F	F	F	F	F	F		

VARIABLE

DESCRIPTION

MID	Material identification. A unique number has to be chosen.
RO	Mass density
EA	E_a , Young's modulus - longitudinal direction
EB	E_b , Young's modulus - transverse direction
EC	E_c , Young's modulus – through thickness direction
PRBA	ν_{ba} , Poisson's ratio ba
PRCA	ν_{ca} , Poisson's ratio ca
PRCB	ν_{cb} , Poisson's ratio cb
GAB	G_{ab} , shear modulus ab
GBC	G_{bc} , shear modulus bc
GCA	G_{ca} , shear modulus ca

AOPT	Material axes option, see Figure 20.1: EQ. 0.0: locally orthotropic with material axes determined by element nodes as shown in Figure 20.1. Nodes 1, 2, and 4 of an element are identical to the Nodes used for the definition of a coordinate system as by *DEFINE_COORDINATE_NODES. EQ. 1.0: locally orthotropic with material axes determined by a point in space and the global location of the element center, this is the a-direction. EQ. 2.0: globally orthotropic with material axes determined by vectors defined below, as with *DEFINE_COORDINATE_VECTOR.
XP YP ZP	Define coordinates of point p for AOPT = 1.
A1 A2 A3	Define components of vector a for AOPT = 2.
V1 V2 V3	Define components of vector v for AOPT = 3.
D1 D2 D3	Define components of vector d for AOPT = 2.
SAT	Longitudinal tensile strength
SAC	Longitudinal compressive strength
SBT	Transverse tensile strength
SBC	Transverse compressive strength
SCT	Through thickness tensile strength
SFC	Crush strength
SFS	Fiber mode shear strength
SAB	Shear strength, ab plane, see below.
SBC	Shear strength, bc plane, see below.
SCA	Shear strength, ca plane, see below.
SFFC	Scale factor for residual compressive strength
AMODEL	Material models: EQ. 1: Unidirectional layer model EQ. 2: Fabric layer model
BETA	Layer in-plane rotational angle in degrees.
PHIC	Coulomb friction angle for matrix and delamination failure
S-DELM	Scale factor for delamination criterion
E_LIMT	Element eroding axial strain

ECRSH	Limit compressive relative volume for element eroding
EEXPN	Limit expansive relative volume for element eroding
OMGMX	Limit damage parameter for elastic modulus reduction
AM1	Coefficient for strain rate softening property for fiber damage in A direction
AM2	Coefficient for strain rate softening property for fiber damage in B direction (For plain weave model only)
AM3	Coefficient for strain rate softening property for fiber crush and punch shear damage
AM4	Coefficient for strain rate softening property for matrix and delamination damage
CR1	Coefficient for strain rate dependent strength properties
CR2	Coefficient for strain rate dependent axial moduli
CR3	Coefficient for strain rate dependent shear moduli
CR4	Coefficient for strain rate dependent transverse moduli

Material Models

Failure models based on the 3D strains in a composite layer with improved progressive failure modeling capability are established for a unidirectional or a plain weave fabric composite layer. They can be used to effectively simulate the fiber failure and delamination behavior under high strain-rate and high pressure ballistic impact conditions.

The unidirectional and fabric layer failure criteria and the associated property degradation models are described as follows. All the failure criteria are expressed in terms of stress components based on ply level strains $(\varepsilon_1, \varepsilon_2, \varepsilon_3, \varepsilon_{12}, \varepsilon_{23}, \varepsilon_{31}) = (\varepsilon_a, \varepsilon_b, \varepsilon_c, \varepsilon_{ab}, \varepsilon_{bc}, \varepsilon_{ca})$. The associated elastic moduli are $(E_1, E_2, E_3, G_{12}, G_{23}, G_{31}) = (E_a, E_b, E_c, G_{ab}, G_{bc}, G_{ca})$. Note that for the unidirectional model, a, b and c denote the fiber, in-plane transverse and out-of-plane directions, respectively, while for the fabric model, a, b and c denote the in-plane fill, in-plane warp and out-of-plane directions, respectively.

Unidirectional lamina damage functions

The fiber failure criteria of Hashin for a unidirectional layer are generalized to characterize the fiber damage in terms of strain components for a unidirectional layer. Three damage functions are used for fiber failure, one in tension/shear, one in compression, and another one in crush under pressure. They are chosen in terms of quadratic strain forms as follows.

Tension/Shear:

$$f_1 - r_1^2 = \left(\frac{E_a \langle \varepsilon_a \rangle}{S_{AT}} \right)^2 + \left(\frac{G_{ab}^2 \varepsilon_{ab}^2 + G_{ca}^2 \varepsilon_{ca}^2}{S_{FS}^2} \right) - r_1^2 = 0 \quad (1)$$

Compression:

$$f_2 - r_2^2 = \left(\frac{E_a \langle \varepsilon_a \rangle}{S_{AC}} \right)^2 - r_2^2 = 0 \quad (2)$$

Crush:

$$f_3 - r_3^2 = \left(\frac{E_c \langle \varepsilon_c \rangle}{S_{FC}} \right)^2 - r_3^2 = 0 \quad (3)$$

where $\langle \rangle$ are Macaulay brackets, S_{AT} and S_{AC} are the tensile and compressive strengths in the fiber direction, and S_{FS} and S_{FC} are the layer strengths associated with the fiber shear and crush failure, respectively. The damage thresholds, r_i , $i=1,2,3$, have the initial values equal to 1 before the damage initiated, and are updated due to damage accumulation in the associated damage modes.

Matrix mode failures must occur without fiber failure, and hence they will be on planes parallel to fibers. Two matrix damage functions are chosen for the failure plane perpendicular and parallel to the layering planes. They have the forms:

Perpendicular matrix mode:

$$f_4 - r_4^2 = \left(\frac{E_b \langle \varepsilon_b \rangle}{S_{BT}} \right)^2 + \left(\frac{G_{bc} \varepsilon_{bc}}{S_{BC0} + S_{SRB}} \right)^2 + \left(\frac{G_{ab} \varepsilon_{ab}}{S_{AB0} + S_{SRB}} \right)^2 - r_4^2 = 0 \quad (4)$$

Parallel matrix mode (Delamination):

$$f_5 - r_5^2 = S^2 \left\{ \left(\frac{E_c \langle \varepsilon_c \rangle}{S_{CT}} \right)^2 + \left(\frac{G_{bc} \varepsilon_{bc}}{S_{BC0} + S_{SRC}} \right)^2 + \left(\frac{G_{ca} \varepsilon_{ca}}{S_{CA0} + S_{SRC}} \right)^2 \right\} - r_5^2 = 0 \quad (5)$$

where S_{BT} and S_{CT} are the transverse tensile strengths, and S_{AB0} , S_{CA0} and S_{BC} are the shear strength values of the corresponding tensile modes ($\varepsilon_b > 0$ or $\varepsilon_c > 0$). Under compressive transverse strain, $\varepsilon_b < 0$ or $\varepsilon_c < 0$, the damaged surface is considered to be “closed”, and the damage strengths are assumed to depend on the compressive normal strains based on the Mohr -Coulomb theory, i.e.,

$$\begin{aligned} S_{SRB} &= E_B \tan(\varphi) \langle -\varepsilon_b \rangle \\ S_{SRC} &= E_C \tan(\varphi) \langle -\varepsilon_c \rangle \end{aligned} \quad (6)$$

where φ is a material constant as $\tan(\varphi)$ is similar to the coefficient of friction. The damage thresholds, r_4 and r_5 , have the initial values equal to 1 before the damage initiated, and are updated due to damage accumulation of the associated damage modes.

Failure predicted by the criterion of f_4 can be referred to as transverse matrix failure, while the matrix failure predicted by f_5 , which is parallel to the layer, can be referred as the delamination mode when it occurs within the elements that are adjacent to the ply interface. Note that a scale factor S is introduced to provide better correlation of delamination area with experiments. The scale factor S can be determined by fitting the analytical prediction to experimental data for the delamination area.

Fabric Lamina Damage Functions

The fiber failure criteria of Hashin for a unidirectional layer are generalized to characterize the fiber damage in terms of strain components for a plain weave layer. The fill and warp fiber tensile/shear damage are given by the quadratic interaction between the associated axial and through the thickness shear strains, i.e.,

$$\begin{aligned} f_6 - r_6^2 &= \left(\frac{E_a \langle \varepsilon_a \rangle}{S_{AT}} \right)^2 + \left(\frac{G_{ca} \varepsilon_{ca}}{S_{AFS}} \right)^2 - r_6^2 = 0 \\ f_7 - r_7^2 &= \left(\frac{E_b \langle \varepsilon_b \rangle}{S_{BT}} \right)^2 + \left(\frac{G_{bc} \varepsilon_{bc}}{S_{BFS}} \right)^2 - r_7^2 = 0 \end{aligned} \quad (7)$$

where S_{AT} and S_{BT} are the axial tensile strengths in the fill and warp directions, respectively, and S_{AFS} and S_{BFS} are the layer shear strengths due to fiber shear failure in the fill and warp directions. These failure criteria are applicable when the associated ε_a or ε_b is positive. The damage thresholds r_6 and r_7 are equal to 1 without damage. It is assumed $S_{AFS} = S_{FS}$, and $S_{BFS} = S_{FS} * S_{BT} / S_{AT}$.

When ε_a or ε_b is compressive, it is assumed that the in-plane compressive damage in the fill and warp directions are given by the maximum strain criterion, i.e.,

$$\begin{aligned} f_8 - r_8^2 &= \left[\frac{E_a \langle \varepsilon'_a \rangle}{S_{AC}} \right]^2 - r_8^2 = 0, \quad \varepsilon'_a = -\varepsilon_a - \langle -\varepsilon_c \rangle \frac{E_c}{E_a} \\ f_9 - r_9^2 &= \left[\frac{E_b \langle \varepsilon'_b \rangle}{S_{BC}} \right]^2 - r_9^2 = 0, \quad \varepsilon'_b = -\varepsilon_b - \langle -\varepsilon_c \rangle \frac{E_c}{E_b} \end{aligned} \quad (8)$$

where S_{AC} and S_{BC} are the axial compressive strengths in the fill and warp directions, respectively, and r_8 and r_9 are the corresponding damage thresholds. Note that the effect of through the thickness compressive strain on the in-plane compressive damage is taken into account in the above two equations.

When a composite material is subjected to transverse impact by a projectile, high compressive stresses will generally occur in the impact area with high shear stresses in the surrounding area between the projectile and the target material. While the fiber shear punch damage due to the high shear stresses can be accounted for by equation (1), the crush damage due to the high through the thickness compressive pressure is modeled using the following criterion:

$$f_{10} - r_{10}^2 = \left(\frac{E_c \langle \varepsilon_c \rangle}{S_{FC}} \right)^2 - r_{10}^2 = 0 \quad (9)$$

where S_{FC} is the fiber crush strengths and r_{10} is the associated damage threshold.

A plain weave layer can be damaged under in-plane shear stressing without occurrence of fiber breakage. This in-plane matrix damage mode is given by

$$f_{11} - r_{11}^2 = \left(\frac{G_{ab} \varepsilon_{ab}}{S_{AB}} \right)^2 - r_{11}^2 = 0 \quad (10)$$

where S_{AB} is the layer shear strength due to matrix shear failure and r_{11} is the damage threshold.

Another failure mode, which is due to the quadratic interaction between the thickness strains, is expected to be mainly a matrix failure. This through the thickness matrix failure criterion is assumed to have the following form:

$$f_{12} - r_{12}^2 = S^2 \left\{ \left(\frac{E_c \langle \varepsilon_c \rangle}{S_{CT}} \right)^2 + \left(\frac{G_{bc} \varepsilon_{bc}}{S_{BC0} + S_{SR}} \right)^2 + \left(\frac{G_{ca} \varepsilon_{ca}}{S_{CA0} + S_{SR}} \right)^2 \right\} - r_{12}^2 = 0 \quad (11)$$

where r_{12} is the damage threshold, S_{CT} is the through the thickness tensile strength, and S_{BC0} and S_{CA0} are the shear strengths for tensile ε_c . The damage surface due to equation (11) is parallel to the composite layering plane. Under compressive through the thickness strain, $\varepsilon_c < 0$, the damaged surface (delamination) is considered to be “closed”, and the damage strengths are assumed to depend on the compressive normal strain ε_c similar to the Coulomb-Mohr theory, i.e.,

$$S_{SR} = E_c \tan \varphi \langle -\varepsilon_c \rangle \quad (12)$$

where φ is the Coulomb's friction angle.

When damage predicted by this criterion occurs within elements that are adjacent to the ply interface, the failure plane is expected to be parallel to the layering planes, and, thus, can be referred to as the delamination mode. Note that a scale factor S is introduced to provide better correlation of delamination area with experiments. The scale factor S can be determined by fitting the analytical prediction to experimental data for the delamination area.

Damage Progression Criteria

A set of damage variables ϖ_i with $i = 1, \dots, 6$, are introduced to relate the onset and growth of damage to stiffness losses in the material. The compliance matrix $[S]$ is related to the damage variables as (Matzenmiller, et al., 1995):

$$[S] = \begin{bmatrix} \frac{1}{(1-\varpi_1)E_a} & \frac{-\nu_{ba}}{E_b} & \frac{-\nu_{ca}}{E_c} & 0 & 0 & 0 \\ \frac{-\nu_{ab}}{E_a} & \frac{1}{(1-\varpi_2)E_b} & \frac{-\nu_{cb}}{E_c} & 0 & 0 & 0 \\ \frac{-\nu_{ac}}{E_a} & \frac{-\nu_{bc}}{E_b} & \frac{1}{(1-\varpi_3)E_c} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{(1-\varpi_4)G_{ab}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{(1-\varpi_5)G_{bc}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{(1-\varpi_6)G_{ca}} \end{bmatrix} \quad (13)$$

The stiffness matrix C is obtained by inverting the compliance matrix, $[C] = [S]^{-1}$.

As suggested in Matzenmiller, et al., (1995), the growth rate of damage variables, $\dot{\varpi}_i$, is governed by the damage rule of the form

$$\dot{\varpi}_i = \sum_j \dot{\phi}_j q_{ij} \quad (14)$$

where the scalar functions $\dot{\phi}_j$ control the amount of growth and the vector-valued functions q_{ij} ($i=1, \dots, 6$, $j=1, \dots, 12$) provide the coupling between the individual damage variables (i) and the various damage modes (j). Note that there are five damage modes for the unidirectional model and seven damage modes for the fabric model

The damage criteria $f_i - r_i^2 = 0$ of equations (1 – 5) and (7 – 13) provide the damage surfaces in strain space for the unidirectional and fabric models, respectively. Damage growth, $\dot{\phi}_i > 0$, will occur when the strain path crosses the updated damage surface $f_i - r_i^2 = 0$ and the strain increment has a non-zero component in the direction of the normal to the damage surface, i.e., $\sum_j \frac{\partial f_i}{\partial \varepsilon_j} \dot{\varepsilon}_j > 0$. Combined with a damage growth function $\gamma_i(\varepsilon_j, \varpi_j)$, $j=1, \dots, 6$, $\dot{\phi}_i$ is assumed to have the form

$$\dot{\phi}_i = \sum_j \gamma_i \frac{\partial f_i}{\partial \varepsilon_j} \dot{\varepsilon}_j \quad (\text{no summation over } i) \quad (15)$$

Choosing

$$\gamma_i = \frac{1}{2} (1 - \phi_i) f_i^{\frac{m}{2}-1} \quad (16)$$

and noting that

$$\sum_j \frac{\partial f_i}{\partial \varepsilon_j} \dot{\varepsilon}_j = \dot{f}_i \quad (17)$$

for the quadratic functions of equations (1) to (5), lead to

$$\dot{\phi}_i = \frac{1}{2}(1 - \phi_i) f_i^{\frac{m-1}{2}} \dot{f}_i \quad (\text{no summation over } i) \quad (18)$$

where ϕ_i is the damage variable associated with the i th failure mode, and m is a material constant for softening behavior.

The damage coupling functions q_{ij} are considered for the unidirectional and fabric models as

$$[q] = [q_{\text{uni}}, q_{\text{fabric}}], \quad (19)$$

$$[q_{\text{uni}}] = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 1 & 0 & 1 \\ 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 \\ 1 & 1 & 1 & 0 & 1 \end{bmatrix}, \quad [q_{\text{fabric}}] = \begin{bmatrix} 1 & 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 0 \\ 0 & 1 & 0 & 1 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 & 1 & 0 & 1 \end{bmatrix}$$

Through equation (14), the above function q_{ij} relates the individual damage variables ϖ_i to the various damage modes provided by the damage functions of the unidirectional and fabric models.

For the unidirectional model, the damage coupling vectors q_{i1} and q_{i2} of equation (19) are chosen such that the fiber tensile/shear and compressive damage of modes 1 and 2 (equations A1 and A2, respectively) provide the reduction of elastic moduli E_a , G_{ab} , and G_{bc} , due to ϖ_1 , ϖ_4 and ϖ_6 , respectively. The coupling vector q_{i3} provides that all the elastic moduli are reduced due to the fiber crush damage of mode 3 (equation A3). For the transverse matrix damage mode 4 (equation A4), q_{i4} provides the reduction of E_b , G_{ab} and G_{bc} , while the through the thickness matrix damage mode 5, q_{i5} provides the reduction of E_c , G_{bc} , and G_{ca} .

For the fabric model, the damage coupling vector q_{i6} , q_{i7} , q_{i8} and q_{i9} are chosen for the fiber tensile/shear and compressive damage of modes 6 to 9 (equations A7 and A8) such that the fiber damage in either the fill or warp direction results in stiffness reduction in the loading direction and in the related shear directions. For the fiber crush damage of mode 10 of equation A9, the damage coupling vector q_{i10} is chosen such that all the stiffness values are reduced as an element is failed under the crush mode. For the in-plane matrix shear failure of mode 11 of equation (10), the stiffness reduction due to q_{i11} is limited to in-plane shear modulus, while the through the thickness matrix damage (delamination) of mode 12, the coupling vector q_{i12} is chosen for the through thickness tensile modulus and shear moduli.

Utilizing the damage coupling functions of equation (19) and the growth function of equation (18), a damage variable ϖ_i can be obtained from equation (14) for an individual failure mode j as

$$\varpi_i = 1 - e^{\frac{1}{m}(1-r_j^m)}, \quad r_j \geq 1 \quad (20)$$

Note that the damage thresholds r_j given in the damage criteria of equations (1 – 11) are continuously increasing functions with increasing damage. The damage thresholds have an initial value of one, which results in a zero value for the associated damage variable ϖ_i from equation (20). This provides an initial elastic region bounded by the damage functions in strain space. The nonlinear response is modeled by loading on the damage surfaces to cause damage growth with increasing damage thresholds and the values of damage variables ϖ_i . After damage initiated, the progressive damage model assumes linear elastic response within the part of strain space bounded by the updated damage thresholds. The elastic response is governed by the reduced stiffness matrix associated with the updated damage variables ϖ_i given in equation (13).

When fiber tensile/shear damage is predicted in a layer by equation (1) or (7), the load carrying capacity of that layer in the associated direction is reduced to zero according to damage variable equation (20). For compressive fiber damage due to equation (2) or (8), the layer is assumed to carry a residual axial load in the damaged direction. The damage variables of equation (20) for the compressive modes have been modified to account for the residual strengths of S_{ACR} and S_{BCR} in the fill and warp directions, respectively.

For through the thickness matrix (delamination) failure given by equation (5) or (11), the in-plane load carrying capacity within the element is assumed to be elastic (i.e., no in-plane damage). The load carrying behavior in the through the thickness direction is assumed to depend on the opening or closing of the matrix damage surface. For tensile mode, $\varepsilon_c > 0$, the through the thickness stress components are softened and reduced to zero due to the damage criteria described above. For compressive mode, $\varepsilon_c < 0$, the damage surface is considered to be closed, and thus, ε_c is assumed to be elastic, while ε_{bc} and ε_{ca} are allowed to reduce to a sliding friction traction of equation (6) or (12). Accordingly, for the through the thickness matrix failure of mode 7 under compressive mode, the damage variable equation is further modified to account for the residual sliding strength S_{SR} .

It is well known that it is difficult to obtain the softening response of most quasi-brittle materials including fiber-reinforced composites. The softening response heavily depends on the set-up and test machines, which can lead to very scattered results. Consequently the choice of damage parameters for each mode becomes an open issue. Generally, smaller values of m make the material more ductile whereas higher values give the material more brittle behavior. A methodology to systematically determine the model material properties for penetration modeling has been successfully established in [3].

The effect of strain-rate on the nonlinear stress-strain response of a composite layer is modeled by the strain-rate dependent functions for the elastic moduli $\{E_{RT}\}$ and strength values $\{S_{RT}\}$, respectively, as

$$\{S_{RT}\} = \{S_0\} \left(1 + C_1 \ln \frac{\{\dot{\varepsilon}\}}{\dot{\varepsilon}_0} \right)$$

$$\{S_{RT}\} = \left\{ \begin{array}{l} S_{AT} \\ S_{AC} \\ S_{BT} \\ S_{BC} \\ S_{FC} \\ S_{FS} \end{array} \right\} \text{ and } \{\dot{\varepsilon}\} = \left\{ \begin{array}{l} |\dot{\varepsilon}_a| \\ |\dot{\varepsilon}_a| \\ |\dot{\varepsilon}_b| \\ |\dot{\varepsilon}_b| \\ |\dot{\varepsilon}_c| \\ \left(\dot{\varepsilon}_{ca}^2 + \dot{\varepsilon}_{bc}^2 \right)^{1/2} \end{array} \right\} \quad (21)$$

and

$$\{E_{RT}\} = \{E_0\} \left(1 + C_2 \ln \frac{\{\dot{\varepsilon}\}}{\dot{\varepsilon}_0} \right)$$

$$\{E_{RT}\} = \left\{ \begin{array}{l} E_a \\ E_b \\ E_c \\ G_{ab} \\ G_{bc} \\ G_{ca} \end{array} \right\} \text{ and } \{\dot{\varepsilon}\} = \left\{ \begin{array}{l} |\dot{\varepsilon}_a| \\ |\dot{\varepsilon}_b| \\ |\dot{\varepsilon}_c| \\ |\dot{\varepsilon}_{ab}| \\ |\dot{\varepsilon}_{bc}| \\ |\dot{\varepsilon}_{ca}| \end{array} \right\} \quad (22)$$

where C_1 and C_2 are the strain-rate constants. $\{E_0\}$ and $\{S_0\}$ are the modulus and strength values of $\{E_{RT}\}$ and $\{S_{RT}\}$, respectively at the reference strain-rate $\dot{\varepsilon}_0 = 1s^{-1}$.

Element Erosion

A failed element is eroded in any of three different ways:

1. If fiber tensile failure in a unidirectional layer is predicted in the element and the axial tensile strain is greater than E_LIMIT. For a fabric layer, both in-plane directions are failed and exceed E_LIMIT.
2. If compressive relative volume (ratio of current volume to initial volume) in a failed element is smaller than ECRSH.
3. If expansive relative volume in a failed element is greater than EEXPN.

Damage History Parameters

Information about the damage history variables for the associated failure modes can be plotted in LSPOST. These additional variables are tabulated below:

#	History Variable		Description	Value	LS-POST Components
	Uni	Fabric			
1	Max (r_1, r_2)	Max (r_6, r_8)	Fiber mode in a	0 - elastic >1- damage thresholds, Equations (1) to (11)	7
2	-	Max (r_7, r_9)	Fiber mode in b		8
3	r_3	r_{10}	Fiber crush mode		9
4	r_4	r_{11}	Perpendicular matrix mode		10
5	r_5	r_{12}	Parallel matrix/ delamination mode		11
6			Element delamination indicator	0 – no delamination 1 – with delamination	12

References

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3. Xiao J.R., Gama, B.A. and Gillespie, J.W., (2005). Progressive damage and delamination in plain weave S-2 glass/SC-15 composites under quasi-static punch shear loading. ASME International Mechanical Engineering Congress. November 5-11, 2005 - Orlando, Florida.