Progressive Damage Modeling of Plain-Weave Composites using LS-Dyna Composite Damage Model MAT162

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Summary:

Progressive damage of plain weave S-2 Glass/SC15 composites under in-plane tension, compression, and shear, through-thickness tension and compression, and transverse interlaminar and punch shear loading is presented for a unit single element using the MAT162 composite damage model in LS-Dyna. While the detail formulation of the MAT162 material model can be found in the Keyword user's manual [1], the main objective of this paper is to describe a methodology to determine a set of softening parameters using a unit single element analysis. The analytical formulation of post-yield damage softening is presented with stress-strain behavior of a single element under different loading conditions. Since MAT162 uses four different softening parameters, i.e., AM1 and AM2 for fiber damage along material directions 1 and 2, AM3 for fiber shear and crush, and AM4 for matrix crack and delamination; the choice of a set of these four AM values is not obvious. The stress-strain plots presented in this paper will serve as an additional user guide to select a set of AM values for a specific material and a specific application.

Unlike linear-elastic design of composite structures with max-stress/strain or quadratic failure theories, modeling the post-yield softening behavior allows one to simulate the energy absorbing capabilities of a composite structure. It is important to choose a set of AM values which represent a material's behavior through single element analyses and validation of the model with other quasi-static and dynamic experiments. A poor choice of the AM values may lead to prediction of either higher or lower energy absorption capabilities of the composite structure. In order to accomplish this objective, the single element analysis is presented with appropriate loading and boundary conditions. Model validation studies simulating static and dynamic experiments can be found in [2], and further studies will be presented elsewhere.

Keywords:
Progressive Damage, Unidirectional and Woven Composites, MAT162, Unit Single Element, Finite Element Analysis

1 Introduction

MAT162 is the state-of-the-art in three dimensional progressive damage modeling of unidirectional (UD) and plain weave (PW) composites using solid elements and explicit analysis in LS-Dyna. This material model was developed on the foundation of earlier orthotropic composite models, i.e., MAT02 and MAT59. The detailed formulation of these material models can be found in the LS-Dyna Keyword manual [1]. The input for MAT162 is presented in Table 1, which is slightly modified from [2]. In addition to nine elastic constants (EA, EB, EC, PRBA, PRCA, PRCB, GAB, GBC, & GCA), this material model uses ten strength parameters (SAT, SAC, SBT, SBC, SCT, SFS, SFC, SAB, SBC, SCA) to define the yield point after linear-elastic deformation, two material parameters (SFFC, PHIC) to define residual strength after compression and Mohr-Coulomb type friction factor, two modeling variables (S_DELM, OMGMX) to define stress concentration at the delamination front and maximum admissible modulus reduction, and three erosion parameters (E_LIMT, E_CRSH, EEXPN) for eroding elements to allow penetration or to create free surfaces. There are five quadratic failure criteria for UD composites and seven failure criteria for PW composites to define different damage modes, e.g., matrix crack, delamination, fiber tension-shear, fiber compression, fiber shear, and composite crush. The most important aspect of MAT162 is the capability of modeling post-damage softening behavior of composites using continuum damage mechanics while degrading the material properties following a connectivity matrix of different damage modes. This method of progressive damage is achieved using an exponential damage function with the softening parameter "AM" for four different damage modes, e.g., AM1 for fiber damage in material direction 1 or A, AM2 for fiber damage in material direction 2 or B, AM3 for fiber crush and punch shear, and AM4 for matrix crack and delamination. In addition, the rate effects on strength properties are modeled with four rate parameters, CERATEs. The values of the damage parameters AM can vary between a large negative and a large positive number, and depending on a specific material behavior, four discrete values need to be chosen to run any numerical simulation. Since a large number of simulations need to be conducted to identify a suitable set of AMs that defines a material behavior, it is usually suggested that these parametric computations be conducted on a single element. UD-CCM has developed a series of single element numerical experiments to perform these parametric simulations which can be found at the official MAT162 website [3].

Table 1: MAT162 Properties and Rate-Independent Parameters for S-2 Glass/SC15 [2]

MID	RO, kg/m^3	EA, GPa	EB, GPa	EC, GPa	PRBA	PRCA	PRCB
162	1850.00	27.50	27.50	11.80	0.11	0.18	0.18
GAB, GPa	GBC, GPa	GCA, GPa	AOPT	MACF			
2.90	2.14	2.14	2	1			
XP	YP	ZP	A1	A2	A3		
0	0	0	1	0	0		
V1	V2	V3	D1	D2	D3	BETA	
0	0	0	0	1	0	0	
SAT, MPa	SAC, MPa	SBT, MPa	SBC, MPa	SCT, MPa	SFC, MPa	SFS, MPa	SAB, MPa
600	300	600	300	50	800	250	75
SBC, MPa	SCA, MPa	SFFC	AMODEL	PHIC	E_LIMT	S_DELM	
50	50	0.3	2	10	0.2	1.20	
OMGMX	ECRSH	EEXPN	CERATE1	AM1			
0.999	0.001	4.0	0.000	2.00			
AM2	AM3	AM4	CERATE2	CERATE3	CERATE4		
2.00	0.50	0.35	0.000	0.000	0.000		

This paper will present the effect of the damage softening parameters AM, on the progressive damage behavior of plain weave composites by conducting parametric simulations on a single element. Parametric simulations will be presented for different loading and boundary conditions, e.g., in-plane tension, compression and shear, through-thickness tension and compression, transverse compression-shear and tension-shear. In addition to the four AMs, the in-plane tensile behavior depends on the limit damage parameter OMGMX and the compressive behavior depends on residual strength parameter SFFC. Results obtained from detail parametric simulations will be presented, and will serve as the database of material behavior for users to choose the required damage parameters for MAT162 simulations.

2 Progressive Damage Modeling in MAT162

Following the suggestion by Matzenmiller et al. [4], the post-damage softening behavior of a composite is modeled by an exponential function with four parameters, i.e., AM1 for fiber damage in material direction 1 or ‘A’, AM2 for fiber damage in material direction 2 or ‘B’, AM3 for fiber crush and punch shear damage, and AM4 for matrix crack and delamination damage. A maximum admissible modulus reduction parameter (OMGMX) is used to define the fraction of modulus reduction, the value of which is less than one, e.g., OMGMX = 0.999. Reduction in modulus is defined by an exponential function given by:

$$\varpi = 1 - e^{\frac{1}{m}\left(1-\left(\frac{\varepsilon}{\varepsilon_y}\right)^m\right)} \tag{1}$$

where, ϖ is the modulus reduction parameter, m is the softening parameter, and ε_y is the yield strain. The post-yield modulus E and stress σ can then be expressed as:

$$E = (1-\varpi)E_0 = E_0\, e^{\frac{1}{m}\left(1-\left(\frac{\varepsilon}{\varepsilon_y}\right)^m\right)} \tag{2}$$

$$\sigma = E\varepsilon = E_0\, \varepsilon\, e^{\frac{1}{m}\left(1-\left(\frac{\varepsilon}{\varepsilon_y}\right)^m\right)} \tag{3}$$

where, E_0 is the input modulus. Dimensionless stress up to and beyond the yield point and can then be expressed as:

$$\frac{\sigma}{\sigma_y} = \frac{\varepsilon}{\varepsilon_y} \quad \text{for} \quad \frac{\varepsilon}{\varepsilon_y} \le 1 \tag{4a}$$

$$\frac{\sigma}{\sigma_i} = \frac{\varepsilon}{\varepsilon_y} e^{\frac{1}{m}\left(1-\left(\frac{\varepsilon}{\varepsilon_y}\right)^m\right)} \quad \text{for} \quad \frac{\varepsilon}{\varepsilon_y} > 1 \tag{4b}$$

Figure 1 shows the dimensionless stress as a function of dimensionless strain defined by Eq. (4) for different m values. For a very high positive value of m, e.g. m = 100, the post-yield stress-strain behavior can be considered as brittle failure. For a near zero value of m, e.g. m = 0.01, the post-yield behaviour is almost perfectly plastic. Values of m in the range 0 < m < 100 show different degrees of post-yield softening behavior.

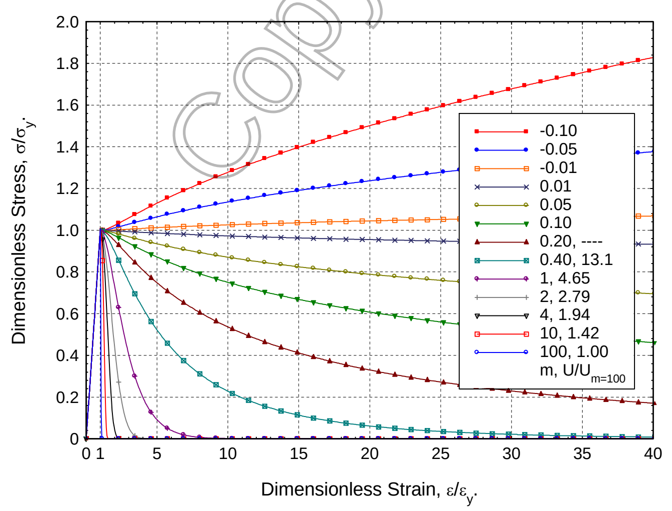


Figure 1: Post-Yield Damage Model Implemented in MAT162

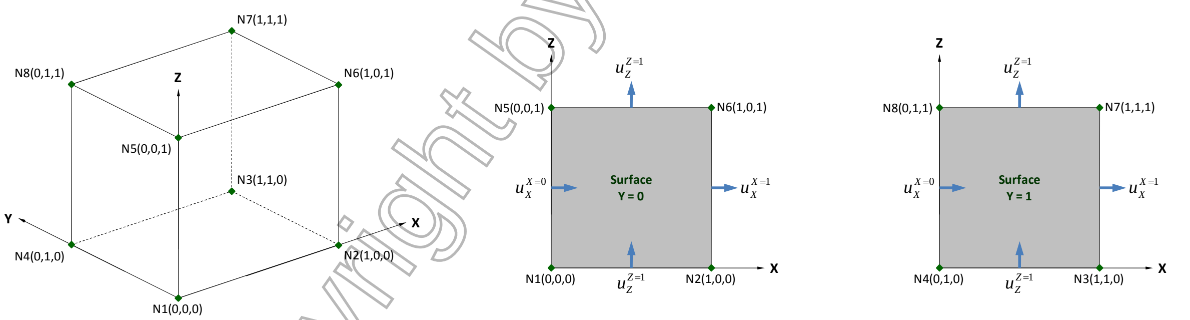
The post damage hardening behavior of a material can be modeled using a negative value of m; however, one must be careful with this parameter since the strain energy will keep increasing until the element is eroded/deleted. Eroding an element with high strain energy is a well known reason for instabilities in explicit computation, and should be avoided if possible. Figure 1 also shows the dimensionless strain energy for different m values, where strain energy for m = 100 is considered as the baseline elastic-brittle failure behavior. As the m value is reduced from 100 to 0.40, the strain energy is increased by a factor of 13.1 as compared to the elastic-brittle material behavior. This formulation of post-damage softening is applied to define tension, compression and shear in all three principal material co-ordinates. The user must conduct a series of single element experiments under uni-axial stress and strain loading conditions and under combined loading. In this paper, we will only present results for several uni-axial stress and combined loading conditions. For additional loading conditions, users are encouraged to visit the official MAT162 website.
<http://www.ccm.udel.edu/Tech/MAT162/Intro.htm>

3 Finite Element Model of the Unit Single Element

An eight node solid element is defined in the first-quadrant with all dimensions equal to one (Figure 2a). The unit single element has six surfaces each containing four nodes as shown in Figure 2. The $i-$ component of displacement on surface $j=0$ or 1 is defined as:

$$u_i^{j=0} \text{ or } u_i^{j=1} \tag{5}$$

where $i=j=$ X, Y, Z. Different combinations of boundary conditions and displacements are applied to simulate uni-axial tension, compression, in-plane shear, transverse interlaminar-shear, and transverse punch-shear deformation of the element. Validated MAT162 material properties and parameters for plain-weave S-2 Glass/SC15 composite are used in the present simulations (Table 1). The stress-strain behavior of the single element under different loading scenarios is presented next.



(a) Single Element (a) Surface Y = 0 (b) Surface Y = 1

Surface X = 0: (N1, N4, N8, N5)
Surface X = 1: (N2, N3, N7, N6)

Surface Y = 0: (N1, N2, N6, N5)
Surface Y = 1: (N4, N3, N7, N8)

Surface Y = 0: (N1, N2, N6, N5)
Surface Y = 1: (N4, N3, N7, N8)

Figure 2: Definition and Nomenclature for the Single Element

4 Results and Discussion

In order to model the progressive damage behavior of the composite, one must start with a set of values for AM1, AM2, AM3, & AM4 (these are four different m values). To be conservative one could set all AM values to 100; however, we will use AM1 = AM2 = AM3 = AM4 = 4.00 as baseline values. Depending on the specific loading conditions, the corresponding value of AM will be varied as a parameter. In the following sections we present the stress-strain behavior of a unit single element under different loading conditions.

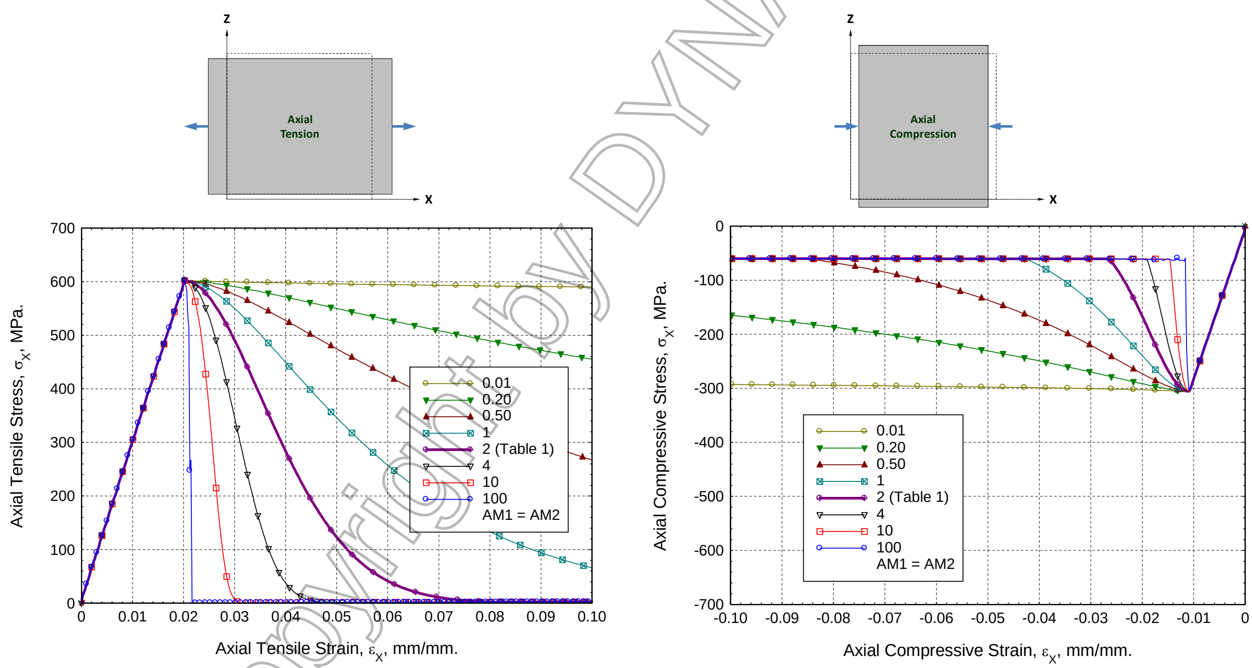
4.1 Tension and Compression along the X-Direction (Uni-Axial Stress)

The uni-axial tension loading along the X-direction is defined by the following boundary conditions and displacement functions.

BCs: $u_Y^{Y=0} = 0$, $u_Z^{Z=0} = 0$ (6a)

Displacement: $u_X^{X=0} = -\frac{1}{2}t\left[H(t) - H(t-t_0)\right]$, $u_X^{X=1} = +\frac{1}{2}t\left[H(t) - H(t-t_0)\right]$ (6b)

where, H represents the Heaviside function. Uni-axial compression can be achieved by switching the signs of the displacement functions. The computation is terminated at time $t_T < t_0$, such that the maximum applied engineering strain is given by $\varepsilon_X^{\max} = t_T / t_0$. The stress-strain behavior under tension and compression along the X-direction is shown in Figure 3. For a plain weave composite $E_X = E_Y$, and thus the loading in the X-direction is the same as the loading in the Y-direction. One can also consider the damage softening behavior to be the same and set AM1 = AM2. Figure 3 shows the post-damage softening behavior for different AM1 = AM2 values in the range 0.01~100 for a fixed value of AM3 = AM4 = 4.0. The stress-strain behavior for AM1 = AM2 = 2.0 reported in Table 1 [2] is highlighted in Figure 3. Large tensile deformation is related to the parameter OMGMX, and the compression behavior with parameter SFFC. Figure 4 outlines these dependences.



(a) X-Tension: AM3 = AM4 = 4.0, OMGMX = 0.999 (b) X-Compression: AM3 = AM4 = 4.0, SFFC = 0.2

Figure 3: Stress-Strain Behavior under Uni-Axial Tension and Compression along X-Direction.

The effect of OMGMX on the tensile stress-strain behavior for AM1 = AM2 = AM3 = AM4 = 4.0 is presented in the first quadrant of Figure 4. If the value of OMGMX is set to a value less than 1, the residual tensile strength behavior can be simulated. However, the limit value of OMGMX should be determined through parametric simulations to match experimental measurements. Most composites show some residual compressive strength behavior during in-plane compression testing, e.g., IITRI compression, and this characteristic behavior is simulated by setting the residual compressive strength to a constant fraction (SFFC) of its original strength. The effect of SFFC on the compressive stress-strain behavior is presented in the third quadrant of Figure 4.

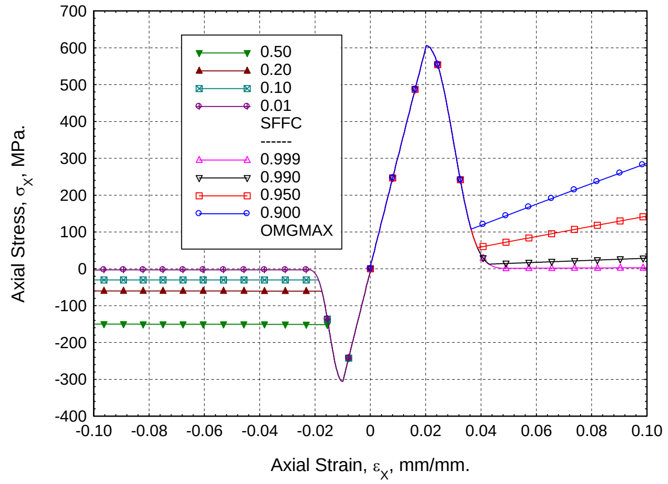


Figure 4: Effect of OMGMX and SFFC on the Stress-Strain Behavior under Uni-Axial Tension and Compression along X-Direction. AM1 = AM2 = AM3 = AM4 = 4.0.

4.2 Through-Thickness Tension and Compression along the Z-Direction (Uni-Axial Stress)

Similar to Eqs. (6a) & (6b), the uni-axial tension along the Z-direction is defined by the following boundary conditions and displacement functions.

BCs: $u_X^{X=0} = 0, \; u_Y^{Y=0} = 0$ (7a)

Displacement: $u_Z^{Z=0} = -\frac{1}{2}t\left[H(t) - H(t-t_0)\right], \; u_Z^{Z=1} = +\frac{1}{2}t\left[H(t) - H(t-t_0)\right]$ (7b)

The compressive loading can be achieved by switching the sign of the displacement functions given by Eq. (7b).

4.2.1 Through-Thickness Tension

Through-thickness tension represents the interlaminar tensile failure behavior of composites as well as delamination crack opening. For 2D woven composites, through-thickness tension can be considered elastic-brittle; however, the effect of toughened resins, interlayers, through-thickness stitching, or 3D Z-reinforcements can show significant post-yield softening behavior. Since the damage parameter AM4 controls the softening behavior for matrix crack and delamination, in Figure 5, AM1, AM2, & AM3 are set to a baseline value of 4 and the parameter AM4 is varied. The stress-strain behavior for AM4 = 0.35 reported in Table 1 [2] is highlighted in Figure 5.

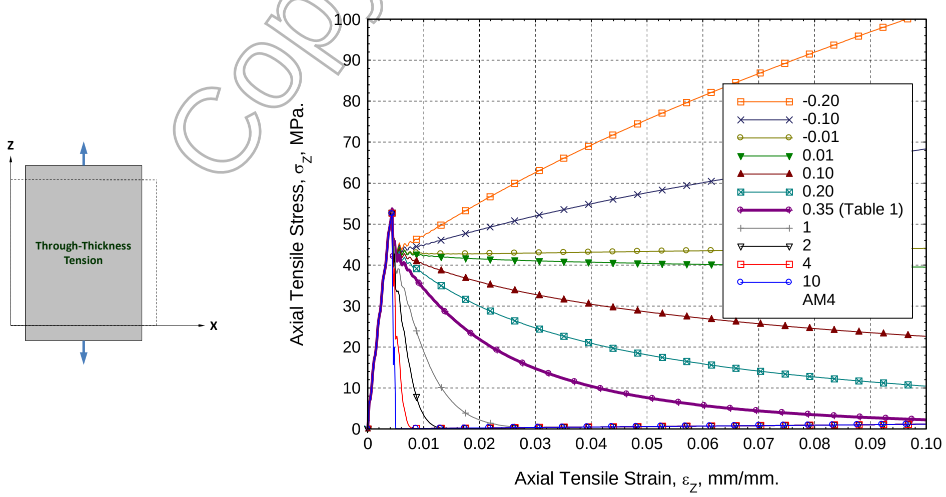


Figure 5: Through-Thickness Tension. AM1 = AM2 = AM3 = 4.0, OMGMX = 0.999.

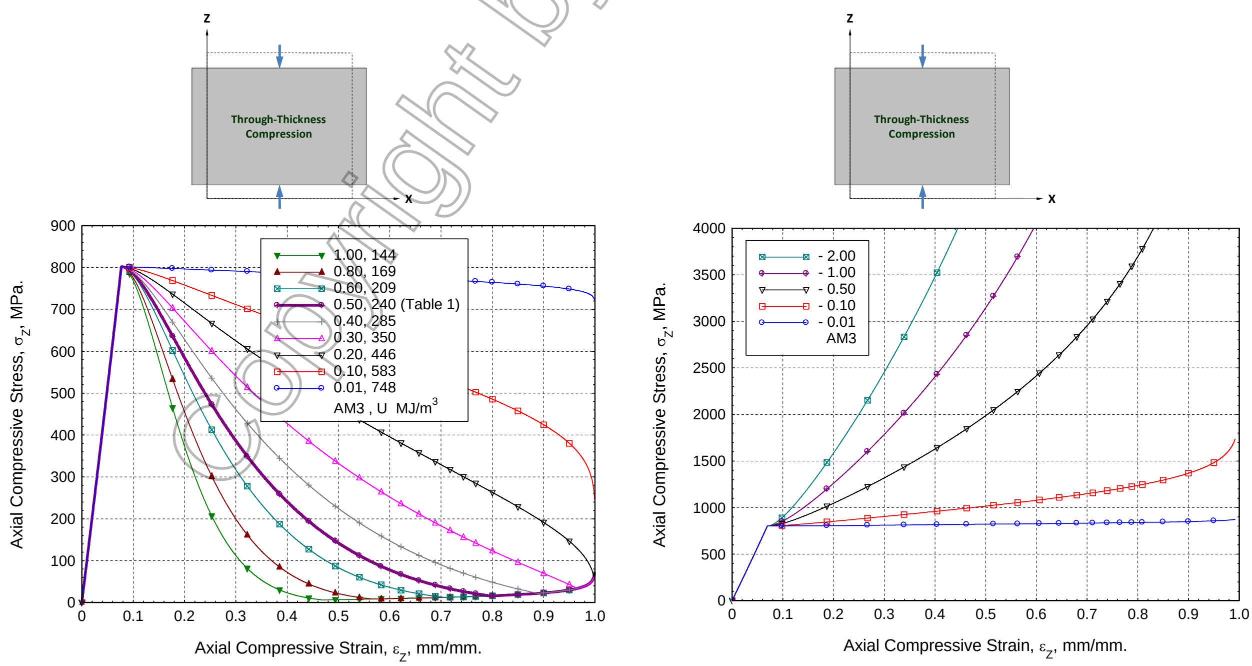
When the delamination criterion is satisfied in an element, the through-thickness stress is immediately reduced to represent crack opening (about 15%) before the application of post-yield softening function. The area under the stress-strain curve is the total strain energy of the single element which can be used to calculate the Mode I strain energy release rate by multiplying with the thickness of a thin element.

$$G_I = U_Z^T \cdot h_C \tag{8}$$

where, G_I is the Mode I energy release rate, U_Z^T is the total strain energy of the unit single element, and h_C is the thickness of a thin element representing a delamination plane. Even though actual delamination does not have any thickness, MAT162 reduces the shear properties of the elements adjacent to one side of a delamination plane. The choice of AM4 should be carefully justified by the user. AM4 << 1 represents very high delamination resistance and should be verified with model experiments, e.g. Mode I fracture toughness tests, or quasi-static punch shear tests [2].

4.2.2 Through-Thickness Compression

Under through-thickness compression loading, delamination criterion is completely suppressed and post-yield softening behavior for fiber crush and punch shear failure modes are controlled by the softening parameter, AM3. Figs. 3a & 3b show the stress-strain behavior under through-thickness compression for AM3 > 0 and AM3 < 0, respectively. The maximum allowable through-thickness strain can be approximated by $\varepsilon_Z^{max} \approx (1 - \mathrm{ECRSH})$, where ECRSH is the limit compressive volume ratio for element erosion. Through-thickness compression tests on composites have revealed that the stress-strain behavior looks similar to that presented in Figure 3b for AM3 < 0. The stress-strain behavior presented for both AM3 > 0 and AM3 < 0 shows that the strain energy stored in a unit single element may vary over a wide range, so the user should choose the value of AM3 to represent a specific composite behavior. We have seen that a small or negative value of AM3 can provide a higher stress value in an element at large deformation and eroding that element may cause instability in computation. New erosion criteria based on element strain energy and soft reduction of stress in the element before element erosion need to be implemented in MAT162, and will remain as a future development effort.



(a) AM3 > 0 (b) AM3 < 0

Figure 6: Through-Thickness Compression. AM1 = AM2 = AM4 = 4.0, OMGMX = 0.999.

4.3 In-Plane and Transverse Interlaminar Shear

4.3.1 In-Plane Shear (XY-Plane)

In-plane shear loading in the XY-plane is obtained by the following displacement functions.

Unit Shear: $$u_X^{Y=0} = -\frac{1}{2}t\left[H(t) - H(t-t_0)\right],\quad u_X^{Y=1} = +\frac{1}{2}t\left[H(t) - H(t-t_0)\right] \tag{9}$$

In the absence of any boundary conditions these displacement functions will generate a rotation of the single element about Z-axis. In order to prevent this rotation, a second set of displacement functions are applied on the same surfaces.

Tension/Compression: $$u_Y^{Y=0} = \mp\frac{\delta}{2}t\left[H(t) - H(t-t_0)\right],\quad u_Y^{Y=1} = \pm\frac{\delta}{2}t\left[H(t) - H(t-t_0)\right] \tag{10}$$

where, $0 < \delta < 1$.

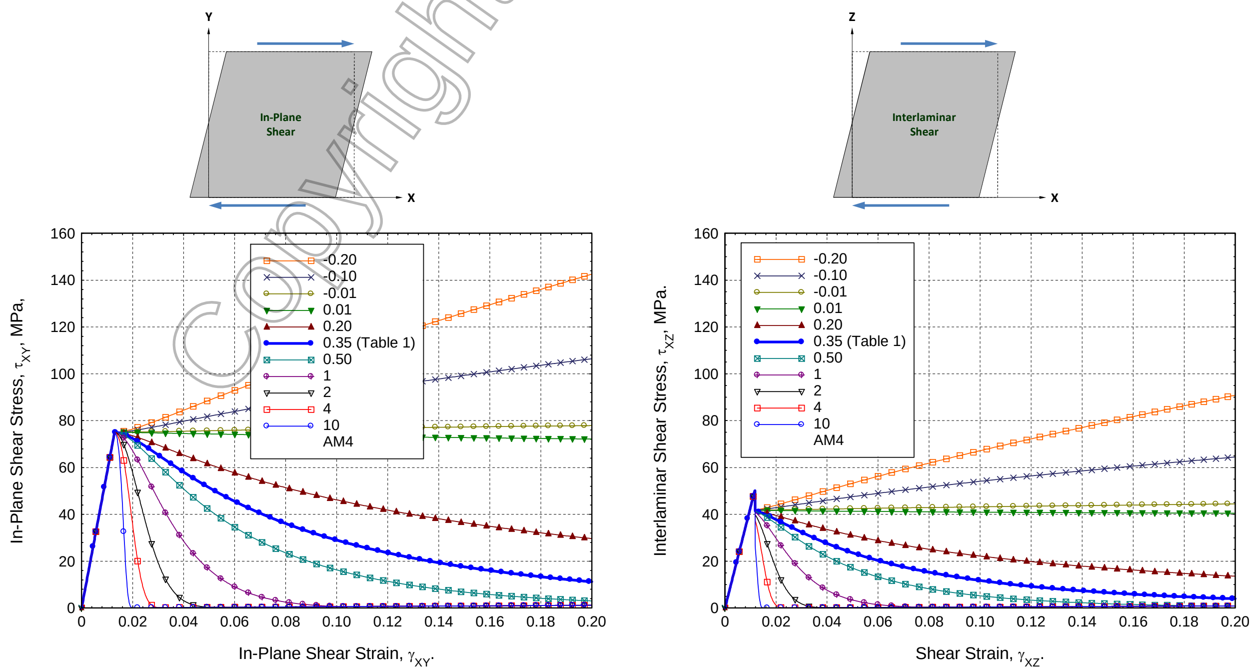
4.3.2 Transverse Interlaminar Shear (XZ-Plane)

Similar to in-plane shear loading, the transverse interlaminar shear loading of the unit single element is defined by the following conditions.

Unit Shear: $$u_X^{Z=0} = -\frac{1}{2}t\left[H(t) - H(t-t_0)\right],\quad u_X^{Z=1} = +\frac{1}{2}t\left[H(t) - H(t-t_0)\right] \tag{11a}$$

Tension/Compression: $$u_Z^{Z=0} = \mp\frac{\delta}{2}t\left[H(t) - H(t-t_0)\right],\quad u_Z^{Z=1} = \pm\frac{\delta}{2}t\left[H(t) - H(t-t_0)\right] \tag{11b}$$

For both in-plane and interlaminar shear loading, the value of $\delta = 0.001$ is chosen. Any values of δ will induce a tension-shear or compression-shear combined loading. Therefore the present loading functions to the unit single element represent combined loading cases. Both in-plane and transverse shear will excite the matrix crack and delamination damage modes. This is why the softening parameter AM4 is considered for parametric study while keeping the other AMs constant, i.e. AM1 = AM2 = AM3 = 4.0.



(a) In-Plane Shear, Matrix Crack

(b) Transverse Interlaminar Shear, Delamination

Figure 7: In-Plane and Transverse Shear. AM1 = AM2 = AM3 = 4.0, OMGMX = 0.999, δ = 0.001.

Results are presented in Figure 7 where the curves for AM4 = 0.3 (Table 1, [2]) are highlighted. The in-plane shear stress-strain behavior is self explanatory, and the transverse interlaminar shear behavior is similar to the through-thickness tension where delamination is the major damage mode.

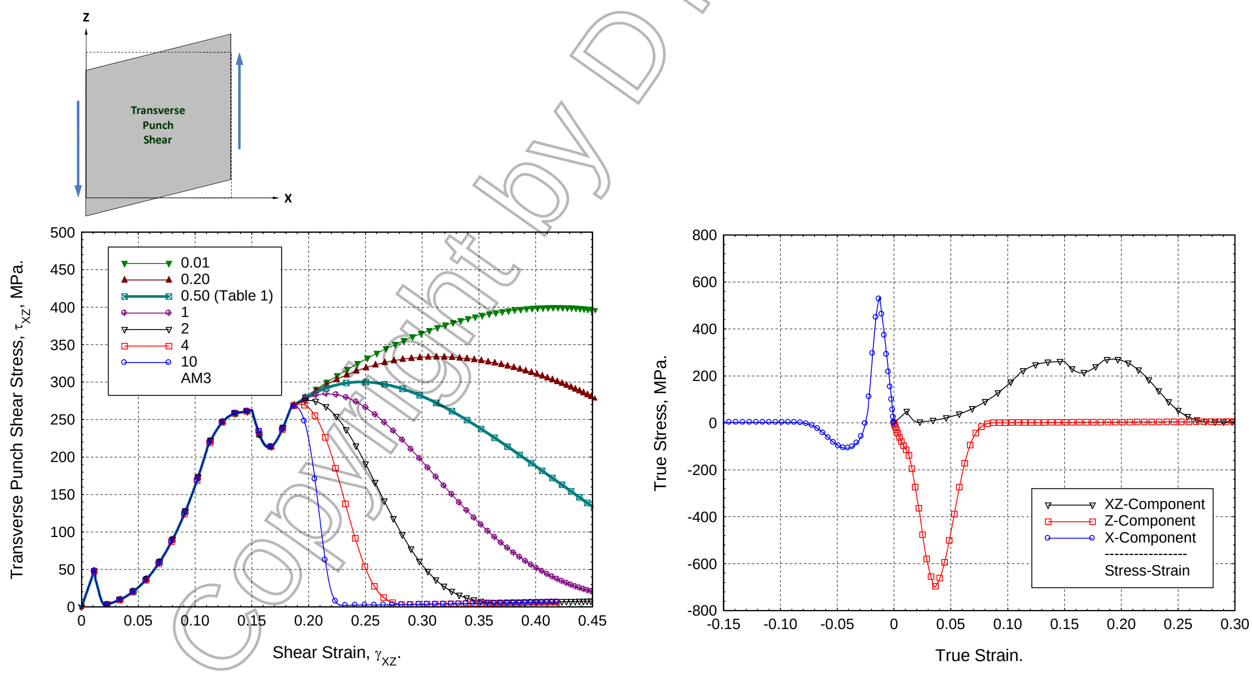
4.4 Combined X-Tension/Compression with Transverse Punch Shear

Transverse punch shear loading represents a combined loading case and can be described by the following set of displacement functions.

Unit Shear: $$u_Z^{X=0} = -\frac{1}{2}t\left[H(t)-H(t-t_0)\right],\quad u_Z^{X=1} = +\frac{1}{2}t\left[H(t)-H(t-t_0)\right] \tag{12a}$$

Tension/Compression: $$u_X^{X=0} = \mp\frac{\delta}{2}t\left[H(t)-H(t-t_0)\right],\quad u_X^{X=1} = \pm\frac{\delta}{2}t\left[H(t)-H(t-t_0)\right] \tag{12b}$$

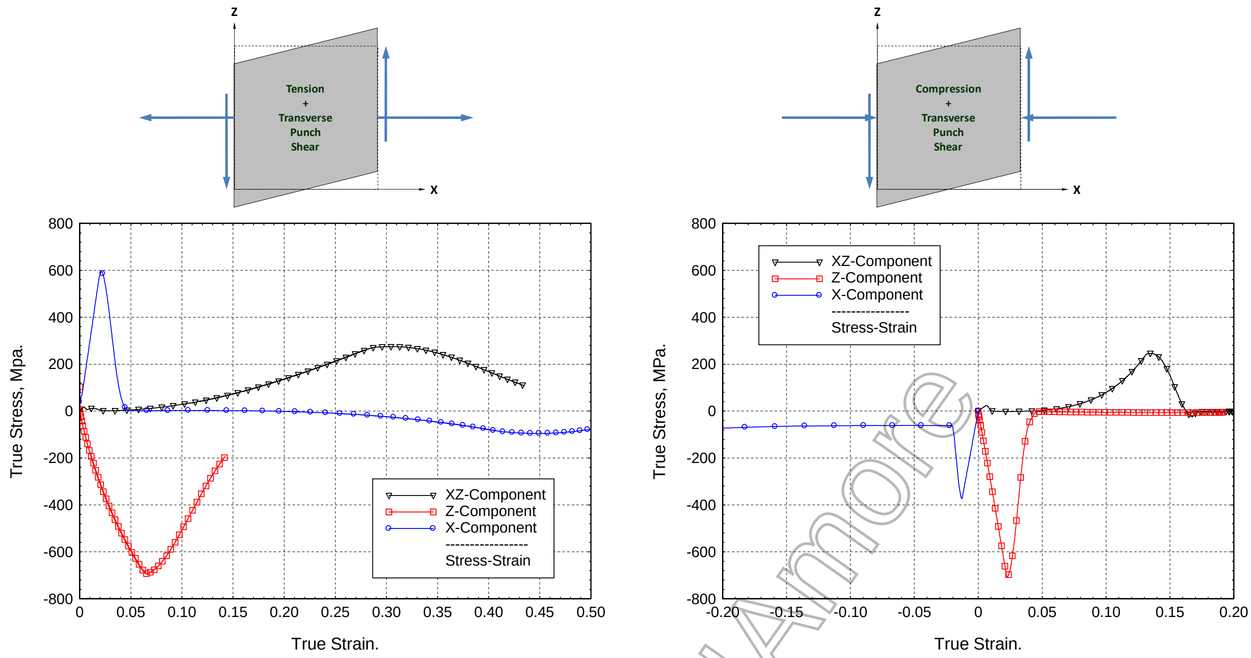
Figure 8a shows the shear stress-strain behavior of the unit single element for different values of AM3. Under transverse punch shear loading, the first failure mode is delamination which appears as a drop in stress to almost zero. As the element undergoes continuous shear deformation, punch shear failure appears as a reduction in stress before the damage softening function kicks in. The punch shear behavior is unique that the value of AM3 < 1 shows significant hardening behavior. It is also important to mention that punch shear deformation of an element will induce axial and through-thickness stresses as presented in Figure 8b for δ = 0.001. The value of $\delta = \pm 1.0$ is used to represent the X-tension XZ-punch shear and X-compression XZ-punch shear loading scenarios which are presented in Figure 9.



(a) AM1 = AM2 = AM4 = 4.0 (b) AM1 = AM2 = AM3 = AM4 = 4.0

Figure 8: Transverse Punch Shear. OMGMX = 0.999, δ = 0.001.

Figure 9 represents a specific loading combination where the shear and axial displacement rates are equal. However, in reality a combined loading may occur for any combination of axial and shear deformation rate.



(a) X-Tension XZ-Punch Shear (b) X-Compression XZ-Punch Shear

Figure 9: Combined Tension/Compression and Transverse Punch Shear.
AM1 = AM2 = AM3 = AM4 = 4.0, OMGMX = 0.999, δ = 1.0.

5 Closing Remarks

This paper presents different features of progressive damage modeling of plain weave S-2 Glass/SC15 composites using a unit single element analyses under different loading and boundary conditions. Progressive composite damage modeling of large deformation, impact, and penetration process is a challenging task because of the number of modeling parameters involved. While the fundamental formulation of MAT162 is described in the Theory and Keyword manuals published by LS-Dyna, the goal of this paper was to demonstrate how unit single element analyses can be used to guide the users to determine a reasonable set of model parameters to start with. It is recommended that the modeling parameters determined from unit single element analyses be further optimized by simulating standard and non-standard test methods, e.g. ASTM standard tests, open hole tension and compression, V-notch shear, through-thickness punch shear at different support spans [5, 6], low velocity impact experiments, Hopkinson bar experiments, and ballistic impact experiments. A methodology for simulating quasi-static punch shear tests in determining damage modeling parameters can be found in Ref. [2]. Simulation of other quasi-static and impact experiments will be presented elsewhere. Keyword program files for all single element analyses presented in this paper are available online at the official MAT162 website hosted by UD-CCM.

<http://www.ccm.udel.edu/Tech/MAT162/Intro.htm>

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