Implementation of a New Continuum Damage Mechanics Model for Composites in LS-DYNA®

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Abstract

A large amount of work has been done to simulate the crashworthiness of composite structures, particularly to evaluate the deformation behavior and to determine the energy absorbing efficiency. However, the existing simulation models generally need to introduce many non-measurable parameters which limited their practical applications. This work focused on the implementation and development of a thermodynamically consistent continuum damage mechanics (CDM) model called Ladevèze model. This model took into account stiffness recovery and inelastic strains, both damage and plastic strains. All the parameters needed in this model can be determined by experiment. Modified Ladevèze models were developed in order to adapt different damage and plasticity evolution laws for different fabric forms of composites. Three different versions of Ladevèze model were implemented in LS-DYNA and their predictive abilities were studied.

1. Introduction

Fiber reinforced composites are widely used in aerospace and automotive industries due to their high stiffness & strength-to-weight ratio, corrosion resistant and energy absorption ability. Many works have been attempted to evaluate the deformation behavior and to determine the energy absorbing efficiency of various composite structures. However, the existing simulation models generally need to introduce many non-measurable parameters [1-2] which limited their practical applications.

In order to build a robust, accurate simulation model for composites, Ladevèze model [3] was evaluated in this study. Ladevèze model is one of the most widely used CDM models for fiber reinforced composites that based on energy potentials [4-12]. It is a meso-model that contains two constituents: single-ply and the interface. Single plies are used to represent intralaminar failure mechanisms, while two-dimensional interfaces are used to transmit tractions from one layer to the next, for the modeling of delamination. The model assumes a uniform state of damage within each meso-constituent [5, 13]. It has already been approved that this mesomodel can be interpreted as the homogenized result of micromodels involving common microdamage mechanisms like mircracking, fiber-matrix debonding and delamination. Since it provides a general formalism, it can be transposed more easily into commercial codes. [14]

Ladevèze model takes into account stiffness recovery and inelastic strains [13]. As shown by Xiao [15], material models that did not take into account the plastic features of composites failures might underestimate the energy absorption capacity of composite structures. Ladevèze model is sufficient to describe the nonlinear or plastic behavior that some thermoset or thermoplastic composites might exhibit, especially in transverse and shear direction [16].

From a practical point of view, the difficulty of most damage models is to characterize a great number of parameters needed to describe the damage behavior. All the parameters needed in the elementary ply of a Ladevèze model can be measured by experiment as listed in ref 3. O′Higgins et al. [17] carried out a detailed experimental test series to determine the input parameters for Ladevèze model on both unidirectional carbon fiber reinforced plastics (CFRP) and glass fiber reinforced plastics (GFRP). The model accurately predicted the responses of axial, transverse and shear direction for both material systems, captured the full extent of the non-linearity in the GFRP transverse response and the shear response of both material systems.

Johnson et al. [18-20] modified Ladevèze model by decoupling the responses of transverse and shear directions. This model was implemented in PAM-CRASH and applied to predict the impact performance of fabric reinforced composites. Pickett et al. [21-22] further modified Johnson’s Ladevèze model by changing the evolution law of shear damage in terms of shear driving force from linear to polynomial function of rank two so that it can be use on biaxial braid composites.

This study was focused on the pre-failure behavior of Ladevèze model on the elementary ply level. Three types of Ladevèze models, i.e. the original Ladevèze model, Johnson’s modified Ladevèze model, and Pickett’s modified Ladevèze model were implemented and studied in LS-DYNA.

2. Theory

Ladevèze model is a CDM model with damage at the elementary-ply scale [3]. It uses damage mechanics to describe the matrix microcracking and fiber/matrix debonding. Delamination was not considered in this study. A plasticity model was introduced to consider inelastic strains induced by damage. The detailed information on the derivation of Ladevèze model in an elementary ply level can be found in ref. 3. For the sake of completion, this section summarized some important aspects of the theory on different versions of Ladevèze model.

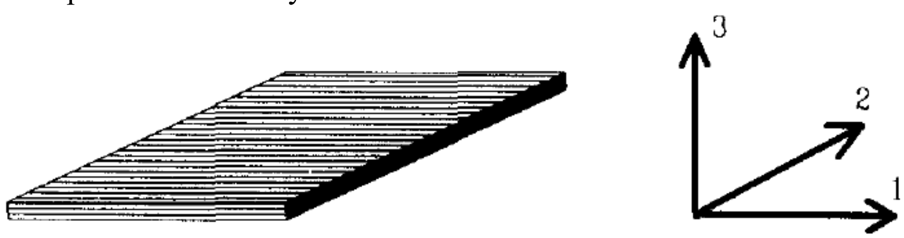


Fig. 1. Elementary ply.

Figure 1. Elementary ply [3]

2.1 Ladevèze model

2.1.1 Damage kinematics of the elementary ply

As shown in Figure 1, a plane-stress state is assumed, thus only the in-plane strains are considered. The damaged material strain energy is written as:

$$E_D = \frac{1}{2}\left[\frac{\sigma_{11}^2}{E_1} - \frac{2\nu_{11}}{E_1}\sigma_{11}\sigma_{22} + \frac{\langle\sigma_{22}\rangle_+^2}{E_2(1-d_2)} + \frac{\langle\sigma_{22}\rangle_-^2}{E_2} + \frac{\sigma_{12}^2}{2G_{12}(1-d_{12})}\right] \quad [1]$$

with

$\langle\sigma_{22}\rangle_+ = \sigma_{22}$ if $\sigma_{22} \geq 0$; otherwise $\langle\sigma_{22}\rangle_+ = 0$

$\langle\sigma_{22}\rangle_- = \sigma_{22}$ if $\sigma_{22} \leq 0$; otherwise $\langle\sigma_{22}\rangle_- = 0$

where d_2 and d_{12} are scalar damage variables that remain constant throughout the ply thickness. The damage forces, a pair of conjugate quantities, Y_{d12} and Y_{d2} are defined by:

$$Y_{d12} = \rho\frac{\partial\psi}{\partial d_{12}} = \frac{\partial E_D}{\partial d_{12}} = \frac{\sigma_{12}^2}{2G_{12}(1-d_{12})^2}$$

$$Y_{d2} = \rho\frac{\partial\psi}{\partial d_2} = \frac{\partial E_D}{\partial d_2} = \frac{\langle\sigma_{22}\rangle_+^2}{2E_2(1-d_2)^2} \quad [2]$$

The damage forces are analogous to energy release rates and they govern the damage development as the energy release rates govern the crack propagation in fracture mechanics. It was shown in [3] that the square root of the damage forces can be quantified much easier from testing data, thus the following parameters are defined:

$$\underline{Y}_{12}(t) = \max\left(\sqrt{Y_{d12}(\tau) + bY_{d2}(\tau)}\right)$$

$$\underline{Y}_2(t) = \max\left(\sqrt{Y_{d2}(\tau)}\right)$$

$$\tau \leq t \quad [3]$$

The damage evolution laws are written as:

$$d_{12} = \frac{\langle\underline{Y}_{12} - Y_{120}\rangle_+}{Y_{12c}} \text{ if } d_{12} < 1 \textit{ and } \underline{Y}_2 < Y_{2s}\text{; otherwise } d_{12} = 1$$

$$d_2 = \frac{\langle\underline{Y}_{12} - Y_{20}\rangle_+}{Y_{2c}} \text{ if } d_2 < 1 \textit{ and } \underline{Y}_2 < Y_{2s}\text{; otherwise } d_2 = 1 \quad [4]$$

Y_{120}, Y_{12c}, Y_{2s}, Y_{20}, Y_{2c} and b are material characteristics which can be determined by experiment.

2.1.2 Plasticity modeling and damage-plasticity coupling

In order to model the inelastic or irreversible deformation of composite ply, the plasticity is considered in the damaged material. The total strain in the ply is split into elastic and plastic parts. A classical plasticity model is used with an elastic domain function and hardening law applied to the effective stresses in the damaged material. Inelastic or strain increments are assumed to be normal to the elastic domain function. [3, 18]

The elastic domain function is defined by:

$$f = \sqrt{\tilde{\sigma}_{12}^2 + a^2\tilde{\sigma}_{22}^2} - R(p) - R_0 \quad [5]$$

where a^2 is a material characteristic constant, R_0 is the initial threshold value for inelastic strain behavior, $p \rightarrow R(p)$ is a material characteristic function determined from cyclic loading tests. $f < 0$ corresponds to a stress state inside the elastic domain where the material may be purely elastic or elastic damaging.

2.1.3 Fiber direction behavior modeling

Experimental results in fiber direction show a brittle linear elastic behavior in tension and a brittle non-linear elastic behavior in compression which was not considered in this study.

2.2 Modified Ladevèze model

Besides the original Ladevèze model, this study also investigated Johnson's and Pickett's modified (or decoupled) Ladevèze model. The major differences are:

1) the modified Ladevèze model decoupled transverse response with shear response;
2) the evolution laws of shear damage in terms of shear driving force were different between Johnson's and Pickett's modified Ladevèze model.

2.2.1 Johnson's modified Ladevèze model

Johnson et al. [18-20] focused on the impact performance of fabric reinforced composites whose longitudinal direction is the same as the transverse direction. Thus they assumed both directions followed similar damage evolution laws and they all decoupled with shear direction. A new set of parameters are defined to governing the damage evolution laws as shown below:

$$\underline{Y}_1(t) = \max\left(\sqrt{Y_{d1}(\tau)}\right)$$
$$\underline{Y}_2(t) = \max\left(\sqrt{Y_{d2}(\tau)}\right)$$
$$\underline{Y}_{12}(t) = \max\left(\sqrt{Y_{d12}(\tau)}\right)$$
$$\tau \le t \quad [6]$$

The damage evolution laws are written as:

$$d_1 = \frac{\langle \underline{Y}_1 - Y_{10}\rangle_+}{Y_{1c}} \text{ if } d_1 < 1 \textit{ and } \underline{Y}_1 < Y_{1s}\text{; otherwise } d_1 = 1$$
$$d_2 = \frac{\langle \underline{Y}_2 - Y_{10}\rangle_+}{Y_{1c}} \text{ if } d_2 < 1 \textit{ and } \underline{Y}_2 < Y_{1s}\text{; otherwise } d_2 = 1$$
$$d_{12} = \frac{\langle \ln\underline{Y}_{12} - \ln Y_{120}\rangle_+}{Y_{12c}} \text{ if } d_{12} < 1 \textit{ and } \underline{Y}_{12} < Y_{12s}\text{; otherwise } d_{12} = 1 \quad [7]$$

The elastic domain function is defined by:

$$f = \sqrt{\tilde{\sigma}_{12}^2} - R(p) - R_0 \quad [8]$$

2.2.2 Pickett's modified Ladevèze model

Pickett et al. [21-22] found Johnson's modified Ladevèze model could not capture the shear behavior of biaxial braided composites. Thus they modified Johnson's Ladevèze model by changing the evolution law of shear damage in terms of shear driving force from linear logarithmic function to polynomial function of rank two as shown in Eqn. 9.

$$d_{12} = b_1\underline{Y}_{12}^2 + b_2\underline{Y}_{12} + b_3 \text{ if } d_{12} < 1 \textit{ and } \underline{Y}_{12} < Y_{12s}\text{; otherwise } d_{12} = 1 \quad [9]$$

b_1, b_2, b_3 are material constants, which can be obtained be fitting experimental data.

2.3 Hardening function

In this paper, an index function is assumed as the hardening function:

$$R(p) = \beta p^m \quad [10]$$

where β and power index *m* are both material properties which can be determined by cyclic tests. Different in tension and compression stiffness was not considered in this study.

The ply level Ladevèze models described in this section were written as user defined material model and implemented in the commercial explicit code LS-DYNA.

3. Material and Simulation Results

In order to verify the implemented Ladevèze models in literature, each of the three models was tested on a single shell element and then compared with the experimental data and predictions in the corresponding literature. The identification procedures of the material properties are detailed in ref. 19 for fabric composites and ref. 3 and ref. 17 for unidirectional composites. Previously, we also did a series of tests to obtain the material properties for 2D triaxial braided composites (2D3A). In order to evaluate the predictive abilities of Ladevèze models, this section presented the simulation results on all the three materials.

3.1 Study on Ladevèze Model

Figure 2 shows a comparison between a pure CDM model and Ladevèze model in the elementary ply level. Both models were assigned the same initial stiffness and strength. However, by introducing in plastic deformation, the overall stiffness of Ladevèze model degraded faster and it reached the maximum stress at a higher strain. Meanwhile, a nonreversible deformation existed in Ladevèze model so that the area under the loading curve or the predicted absorbed energy was larger than the pure CDM model.

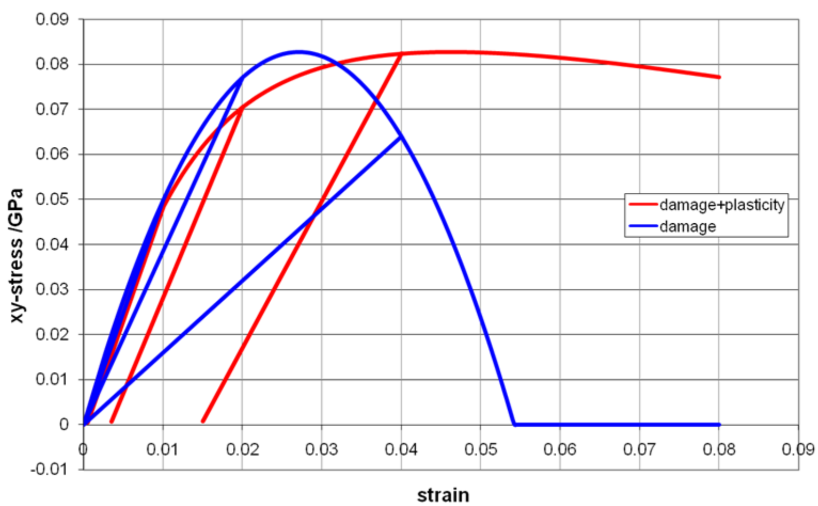
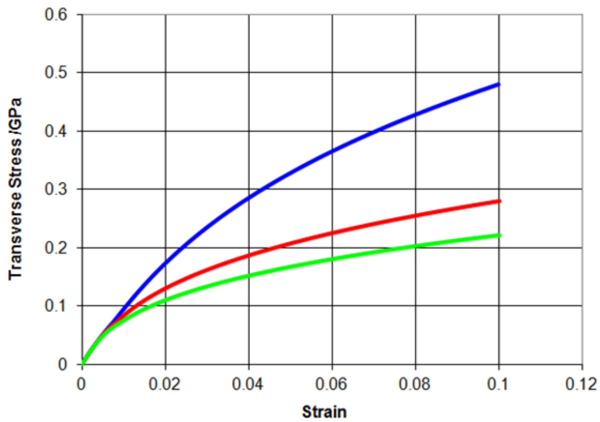
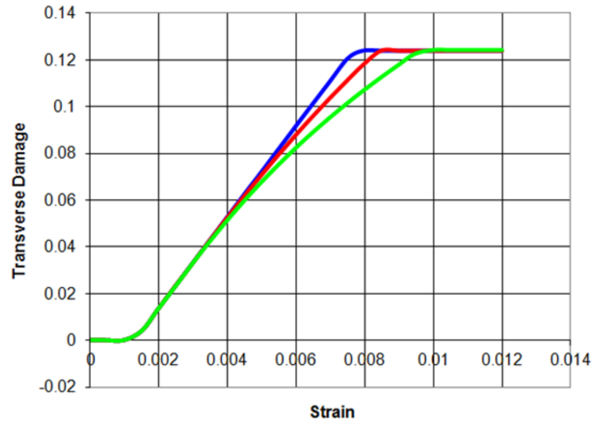


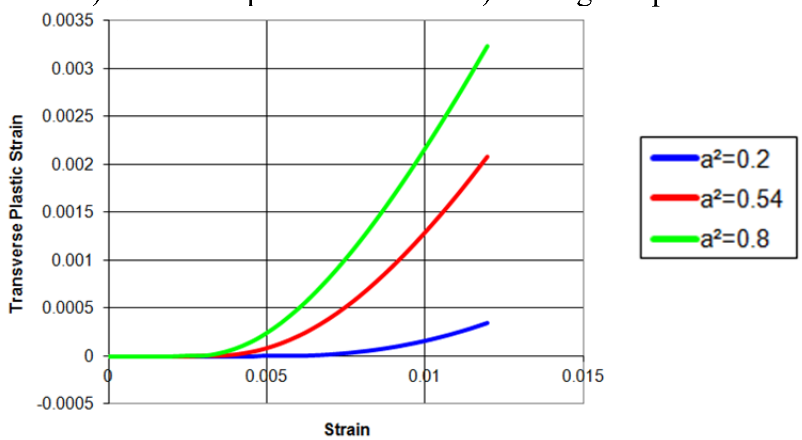
Figure 2. Comparison between a pure CDM model and Ladevèze model.

As shown in Eqn. 3 and Eqn. 5, the two coupling factors, b and a, were both applied on the transverse stresses. The pure shear response was merely affected by the variation of these factors. Therefore, the coupling effects can be studied based on the predicted transverse response. As shown in Fig. 3, decreasing a^2 from 0.2 to 0.8 resulted in stronger transverse responses. This is because the plastic strain develops very slowly under smaller a as shown in Fig. 3c while the damage grows just slightly quicker than the ones under larger a. Therefore, under the same amount of deformation, larger non-plastic strains resulted in higher stresses.





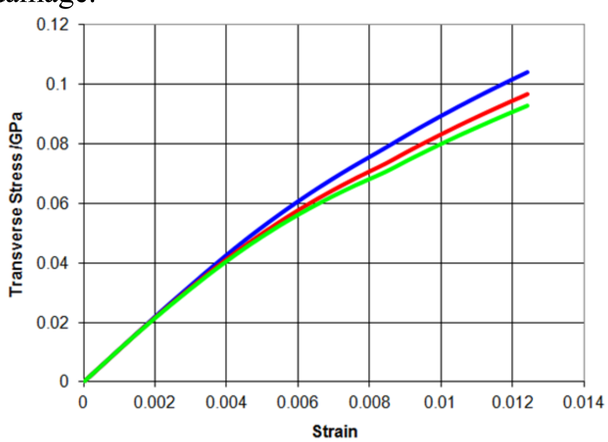
a) Stress response b) Damage response

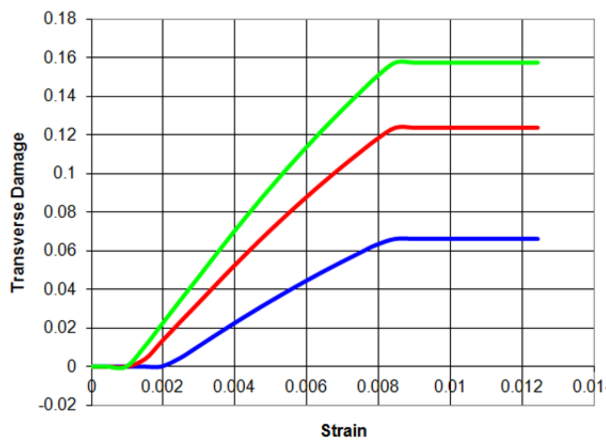


c) Plastic strain response

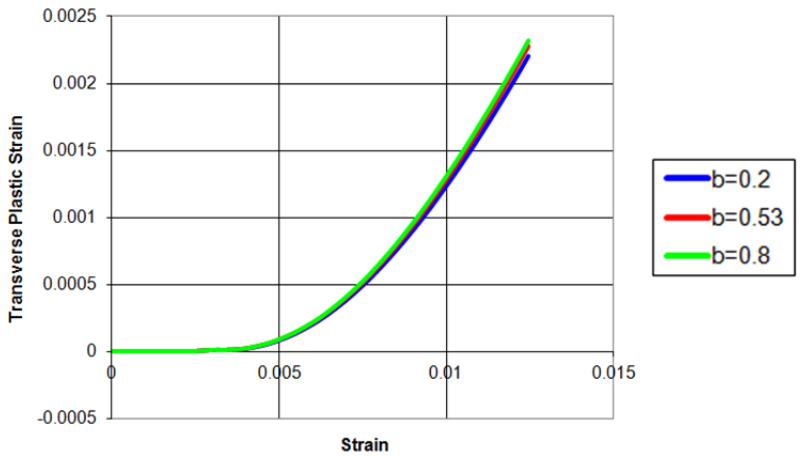
Figure 3. Study on plasticity coupling factor.

Similarly, as shown in Fig. 4, a smaller *b* also resulted in a stronger transverse stress response. This is because a smaller *b* slows down the growth of damage in the transverse direction. The development of plasticity, however, is merely affected by the variation of damage coupling factor. It should be noticed that the small variation in the stress response is due to the small damage studied in this case. The differences between the stresses can be much larger under large damage.





a) Stress response b) Damage response



c) Plastic strain response

Figure 4. Study on damage coupling factor.

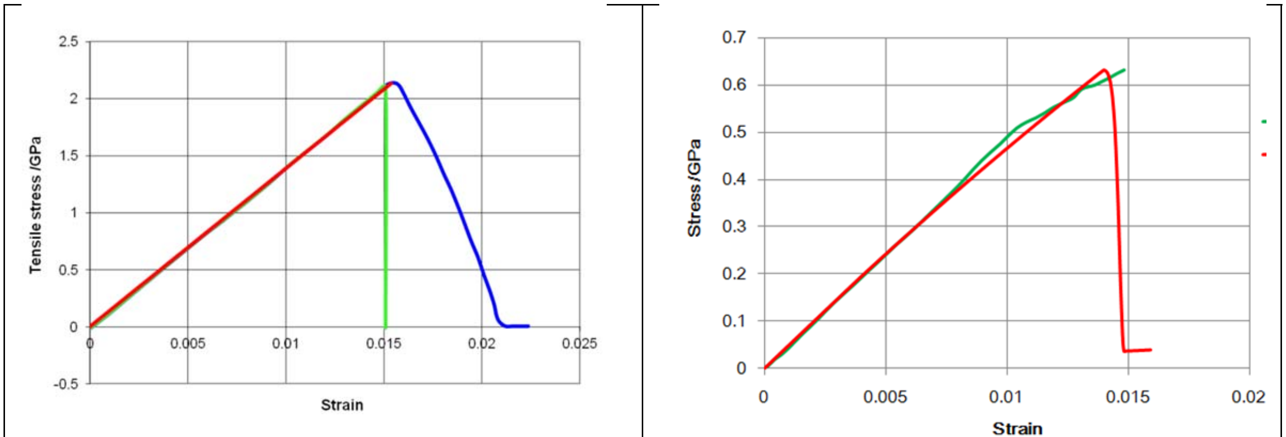
Overall, smaller values of both coupling factors result in stronger responses in the transverse and thus an off-axis direction. The difference is that smaller *a* works by slowing down the plasticity evolution while smaller *b* works by slowing down the damage growth.

3.2 Predictive Ability of Ladevèze Model

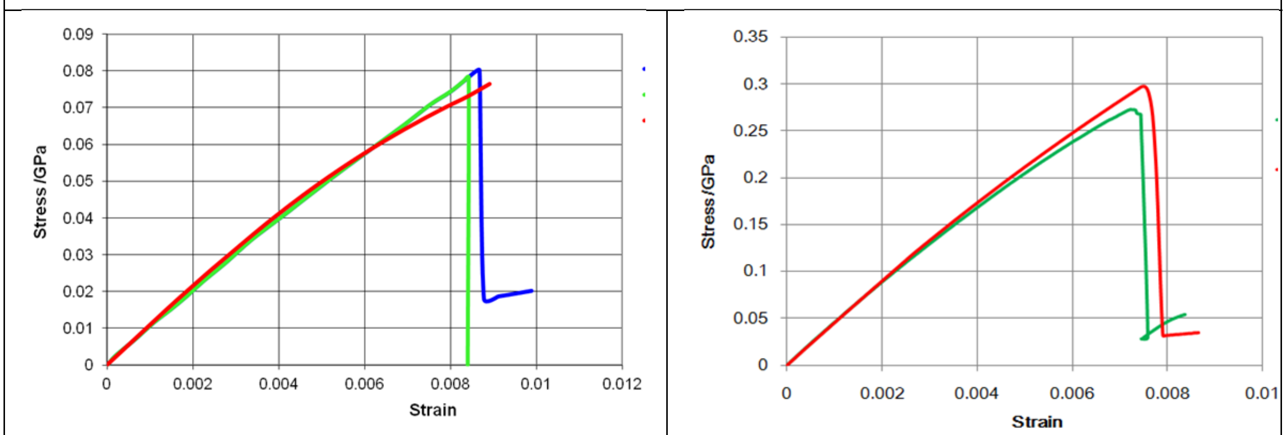
Ladevèze model was designed for unidirectional composites but could be used on many other materials like 2D3A. These materials share very similar material behaviors: axial direction is brittle while transverse direction and shear direction are coupled. O'Higgins et al. [17] carried out a detailed experimental test series to determine the input parameters for Ladevèze model on unidirectional CFRP while we did similar tests on 2D3A.

As shown in Fig. 5, in the axial direction, both simulations matched the experiment results very well since the materials behaved linearly before failure. In the transverse direction and shear direction, Ladevèze model deviated away a little from the experimental results, but generally the differences stayed in a reasonable range. Thus in general, Ladevèze model is able to capture the mechanical responses of both unidirectional composites and 2D3A in all three major directions.

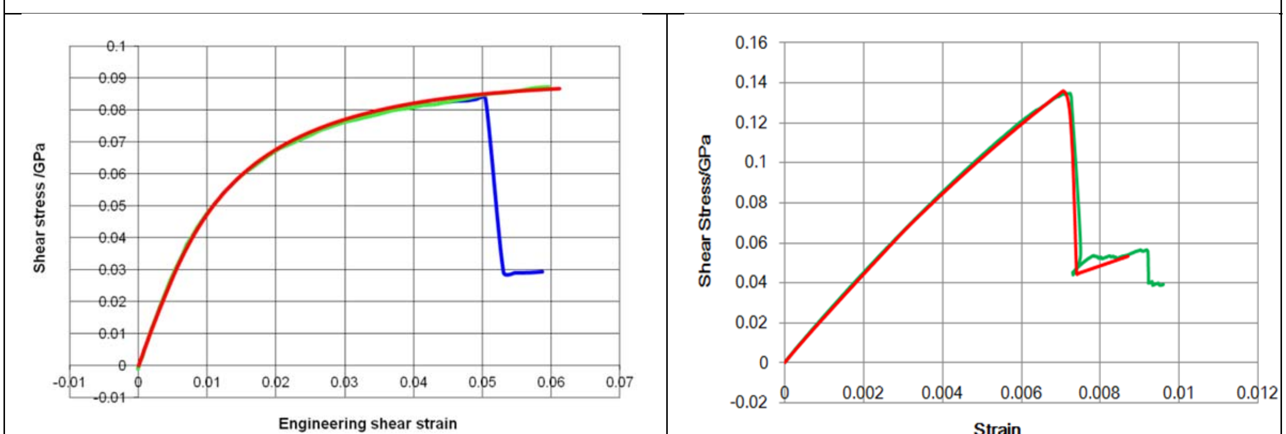
Unidirectional CFRP	2D3A
Experiment OHiggins' simulation Ladeveze model in LS-DYNA	Experiment Simulation



(a) Axial direction



(b) Transverse direction

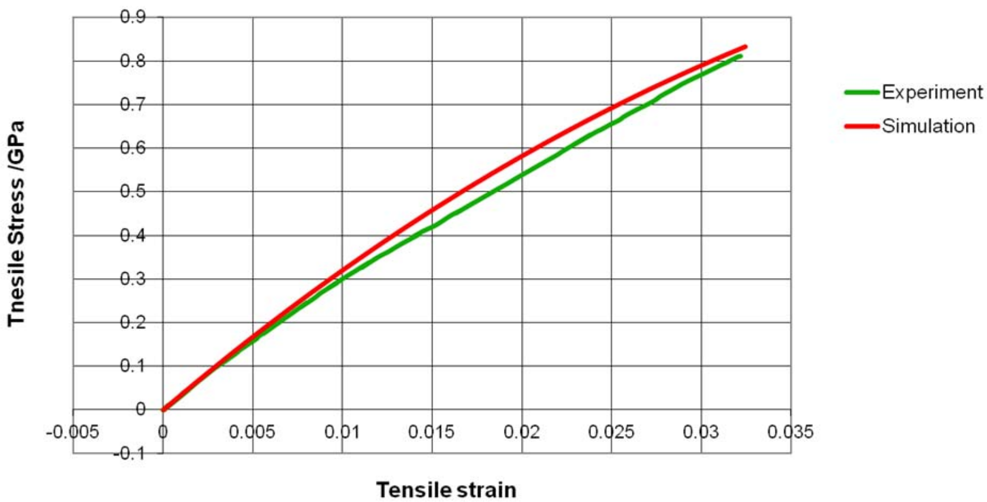


(c) Shear direction

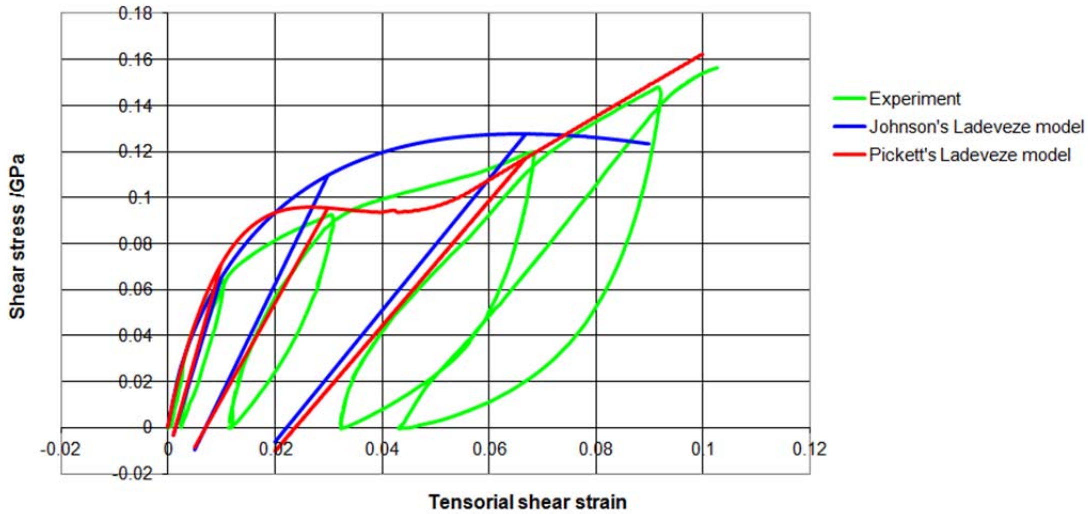
Figure 5. Comparison of simulation results of Ladevèze model and experimental data on the tensile stress-strain response of unidirectional CFRP and 2D3A in three major directions

3.3 Predictive Ability of Modified Ladevèze Models

Johnson's modified Ladevèze model was firstly used to simulate the mechanical response of fabric composites. The comparisons between the simulation results and experimental data are shown in Fig. 6. As shown, in the axial direction, Johnson's modified Ladevèze model could simulate the material response very well. However, a certain deviation was found in the shear direction as presented in Fig. 6b. Johnson's modified Ladevèze model over-predicted the testing results by as large as 20% between strain 0.02~0.07 and the model couldn't simulate the hardening behavior at high strain. The mismatch in Fig. 6b can be explained by several reasons: firstly, 'scissor effect' at high strain may largely affect the shear properties that determined by tensile tests on $\pm 45^o$ specimen; secondly, the damage evolution laws are highly dependent on the unloading process, thus unavoidable error may results from their sensitivity to time and the experimental equipment; thirdly, the current damage evolution law itself may be not good enough to describe the damage evolution process of fabric composites. Pickett and Johnson noticed the aforementioned results when working with woven composites and biaxial braided composites [12]. They modified the damage evolution law from logarithmic to polynomial functions to better fit the shear behavior. Figure 6b compared these two modified Ladevèze models with experiment results. As shown, Pickett's modified Ladevèze model can better predict the shear response overall. After the first peak, Pickett's modified Ladevèze model composed of a softening phase and a hardening phase that matched with experiment finding. Thus, it was able to capture the 'scissor effect' at high strain.



a) Tensile stress-strain response of 0^o fabric composites



b) Tensile stress-strain response of ±45° fabric composites

Figure 6. Comparison of experimental data with simulation results on a) tensile stress-strain response of 0° fabric composites; b) tensile stress-strain response of ±45° fabric composites

4. Conclusion

Three types of Ladevèze models, i.e. the original Ladevèze model, Johnson's simplified Ladevèze model, and Pickett's modified Ladevèze model were implemented in LS-DYNA as user material models. These models were used to investigate the response of an elementary composite ply. The results showed that the original Ladevèze model was applicable to both unidirectional composites and 2D3A since it accurately predicted their responses in all three tested directions. The two modified Ladevèze model could be applied to fabric, woven and biaxial braided composites. However, Pickett's modified Ladevèze model could better predict the overall shear response by successfully capturing its softening phase and hardening phase.

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