Delamination Prediction of Uni-Directional Composite Laminates using Shell Elements and a Strain Rate Dependent Micro-mechanical Material Model

Sandeep Medikonda[1], Ala Tabiei[1]
[1]*University of Cincinnati, Cincinnati, OH, USA*

Abstract

The effectiveness of studying inter-laminar delamination in composites with the help of newly formulated thickness-stretch shell elements (ELFORM=25) as compared to the traditional plane-stress shell elements (ELFORM=2) has been investigated using LS-DYNA®. A strain-rate dependent micro-mechanical material model using ply-level progressive failure criteria has been used to simulate the initiation and propagation of delamination. The numerical delamination growth has been qualitatively analyzed against the experimental C-scan images for multiple impact events on a T800H/3900-2 CFRP plate. As an addition to the capability of the micro-mechanical material model, a methodology of assigning physical significance to the choice of damage parameters has been presented.

Keywords: Unidirectional composites; Micro-mechanical model; Continuum damage mechanics; Delamination; Finite Element Method; LS-DYNA

1. Introduction

Delamination is an inter-laminar failure mode that is critical in characterizing the overall response of Uni-Directional Composites (UDC). Predicting delamination failure accurately in LS-DYNA using standard shell element formulations is a challenge as this failure mode is dependent on the stresses in the through-thickness direction.

Historically, LS-DYNA [1] has only permitted the use of standard shell element formulation where the Z-Stress is zero. However, recently developed 'thickness-stretch' shell formulations (ELFORM = 25, 26) which utilize 3D constitutive models are believed to simulate the delamination behavior more accurately because of the presence of a non-zero Z-stress. In the current work, this behavior has been tested using a strain-rate dependent micro-mechanical constitutive model [3] with progressive post-failure criteria and is implemented as an UMAT (user-material model) in LS-DYNA. The nonlinear, strain-rate dependent behavior of the resin in this model is captured using the modified Goldberg-Stouffer visco-plastic constitutive relations [4]. As discussed in [5], it is well known that the strain softening damage parameter which accounts for the progressive post-failure behavior of the composite is difficult to determine. Hence, a procedure of characterizing the damage variables from the strain energy released is discussed.

The current paper is organized as follows: section 2 discusses the theory behind the micro-mechanics of the uni-directional composite material model. Section 3 presents a parameter estimation procedure for the damage variables. Section 4 compares the delamination results with the experimental results from Williams and Vaziri et al. [2]. Lastly, section 5 concludes with the learnings from this work.

2. Micro-mechanics of the uni-directional composite (UDC)

The representative volume cell (RVC) used to develop the micro-mechanical relations is shown in figure (1). The current RVC is the same as the one discussed by Tabiei and Babu [3]. However for completeness the micro-mechanics relations are briefly discussed here. The fibers are assumed to be of square cross-section for computational efficiency since this model is implemented in an explicit FE code which uses very small time steps for simulations. The unit cell is divided into three sub-cells: one fiber sub-cell, denoted as ***f***, and two matrix sub-cells, denoted as $\boldsymbol{M_A}$ and $\boldsymbol{M_B}$ respectively. The three sub-cells are grouped into two parts: material part ***A*** consists of the fiber sub-cell ***f*** and the matrix sub-cell $\boldsymbol{M_A}$, and material part ***B*** consists of the remaining matrix $\boldsymbol{M_B}$. The dimensions of the unit cell are 1 × 1 unit square. The dimensions of the fiber and matrix sub-cells are denoted by W_f and W_m respectively as shown in figure (1) and defined as shown below:

$$W_f = \sqrt{V_f}\ ; \quad W_m = 1 - W_f \qquad \text{….. (1)}$$

where, V_f is the fiber volume fraction. As explained in section 2.5 below, effective stresses in the RVC are determined from the sub-cell values in two phases: first, stresses in fiber ***f*** and matrix $\boldsymbol{M_A}$ are combined to obtain effective stresses in part ***A*** which are then combined with stresses in matrix $\boldsymbol{M_B}$ to obtain the effective RVC stresses.

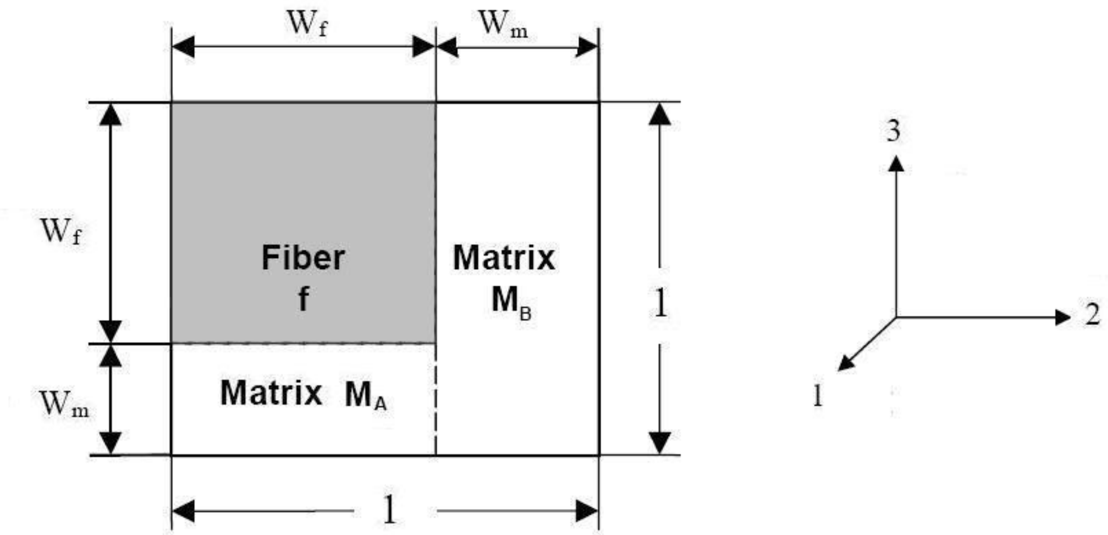

Figure (1): A representative volume cell of unidirectional fiber reinforced polymer composite

2.1. Viscoplastic Constitutive Relations for Matrix Material

The strain rate dependent behavior of a polymer matrix composite is mainly attributed to the viscoplastic nature of the resin component. Hence, strain-rate dependency is incorporated in the current model by using the viscoplastic relationship developed by Goldberg and Stouffer [4] for the matrix constituent (sub-cells $\mathbf{M}_{\boldsymbol{A}}$ and $\mathbf{M}_{\boldsymbol{B}}$). Goldberg and Stouffer developed this constitutive relationship for resins using the state variable approach and used it in their material model for unidirectional composites. They defined their state variable as an internal stress, which evolved with stress and inelastic strain and represented the average effects of the deformation mechanisms. For completeness, the Goldberg-Stouffer relations are discussed briefly in this section. Further details about the relations can be found in [4].

The total strain rate is assumed to be the sum of elastic and inelastic strain rates. The elastic strain rate is equal to the ratio of stress rate to Young's modulus of the material while the inelastic strain rate is defined to be proportional to the exponential of the overstress, the difference between the applied stress and the tensorial internal stress state variable. It is given by the relation:

$$\dot{\varepsilon}_{ij}^{I} = D_0 \exp\left[-\frac{1}{2}\left(\frac{Z_0^2}{3K_2}\right)^n\right]\frac{S_{ij}-\Omega_{ij}}{\sqrt{K_2}} \quad \text{….. (2)}$$

where $\dot{\varepsilon}_{ij}^{I}$, Ω_{ij} are the components of inelastic strain rate, and internal stress respectively, D_0 is a scale factor representing maximum inelastic strain rate, n is a variable which controls rate dependence of the deformation response, Z_0 represents the isotropic, initial hardness of the material before any load is applied, S_{ij} are components of the deviatoric stress tensor given by the relation:

$$S_{ij} = \frac{\sigma_{ij} - \delta_{ij}\sigma_{kk}}{3} \quad \text{….. (3)}$$

where, σ_{ij} are the components of stress, and δ_{ij} is Kronecker's delta. K_2 in equation (2) is defined as an effective stress given by the relation:

$$K_2 = \frac{1}{2}\left(S_{ij} - \Omega_{ij}\right)\left(S_{ij} - \Omega_{ij}\right) \quad \text{….. (4)}$$

and represents the second variant of the overstress tensor. The procedure for determining the resin material constants can be found in [4].
The internal stress rate is given by the relation:

$$\dot{\Omega}_{ij} = \frac{2}{3}q\Omega_m\dot{\varepsilon}_{ij}^{I} - q\Omega_{ij}\dot{\varepsilon}_{e}^{I} \quad \text{….. (5)}$$

where Ω_{ij}, $\dot{\Omega}_{ij}$, and $\dot{\varepsilon}_{ij}^{I}$ are components of internal stress, internal stress rate, and inelastic strain rate respectively and $\dot{\varepsilon}_{e}^{I}$ is effective inelastic strain rate given by the relation:

$$\dot{\varepsilon}_{e}^{I} = \sqrt{\frac{2}{3}\dot{\varepsilon}_{ij}^{I}\dot{\varepsilon}_{ij}^{I}} \quad \text{….. (6)}$$

It is to be noted that equations (2) through (6) actually formulate one differential equation per component of the tensorial parameters involved or one first order tensorial differential equation which has no closed form solution. Hence, a numerical solution is obtained at each time step of the explicit FE simulation by integrating using the 4th order Runge-Kutta method.

2.2. Constitutive Relations of Fibers

The fibers are assumed to be linearly elastic materials which are initially transversely isotropic but become orthotropic with damage evolution. It is assumed that damages to the fibers are a result of direct stresses applied on them only and that shear stresses do not cause any damages. The damages are assumed to be oriented in the material directions of the fibers and independent. The constitutive relations of the fibers can be written in matrix form as:

$$\{\sigma\}^f = [C_f]\{\varepsilon\}^f \qquad \text{….. (7)}$$

where, $\lfloor C_f \rfloor$ is the stiffness matrix which can be partitioned into direct and shear stress stiffness matrices as follows:

$$[C_f] = [S_f]^{-1} = \begin{bmatrix} [S_{fd}]^{-1} & [0]_{3\times 3} \\ [0]_{3\times 3} & [S_{fs}]^{-1} \end{bmatrix} \qquad \text{….. (8)}$$

The direct stress compliance matrix, whose inverse is the direct stress stiffness matrix, should be symmetric and the following relationship should be obeyed:

$$\frac{\nu_{ij}}{E_i} = \frac{\nu_{ji}}{E_j} \quad , \quad i, j = 1,2,3 \text{ and } i \neq j \text{ (no summation)} \qquad \text{….. (9)}$$

The direct and shear stress compliance matrices in terms of the properties of the fibers are:

$$[S_{fd}] = \begin{bmatrix} \dfrac{1}{(1-d_1)E_1} & -\sqrt{\dfrac{\nu_{12}}{(1-d_1)E_1}\dfrac{\nu_{21}}{(1-d_2)E_2}} & -\sqrt{\dfrac{\nu_{12}}{(1-d_1)E_1}\dfrac{\nu_{21}}{(1-d_3)E_2}} \\ & \dfrac{1}{(1-d_2)E_2} & -\dfrac{\nu_{23}}{\sqrt{(1-d_2)E_2(1-d_3)E_2}} \\ Symm. & & \dfrac{1}{(1-d_3)E_2} \end{bmatrix} \qquad \text{….. (10)}$$

$$[S_{fs}] = \begin{bmatrix} \dfrac{1}{G_{12}} & 0 & 0 \\ & \dfrac{1}{G_{23}} & 0 \\ Symm. & & \dfrac{1}{G_{o12}} \end{bmatrix} \qquad \text{….. (11)}$$

where E_1, E_2 are the longitudinal and transverse moduli of the fibers respectively, ν_{ij}, $i, j = 1,2,3$ and $i \neq j$, are its Poisson's ratios, G_{o12}, G_{12} are its initial and strain-rate dependent in-plane shear moduli respectively, G_{23} is its transverse shear moduli, and d_i, $i = 1,2,3$, are damage parameters given in the following section on progressive failure modeling. In-plane shear is considered as a parameter which is strain-rate dependent. Hence, the shear modulus G_{12} is given by the following relation:

$$G_{12} = a_G s_s + G_{o12} \qquad \text{….. (12)}$$

$$s_s = \frac{1}{t}\int_0^t \log\left(\frac{|\dot{\varepsilon}_{12}|}{\dot{\varepsilon}_o}\right) \mathrm{d}t \qquad \text{….. (13)}$$

where a_G is a parameter which expresses the strain-rate sensitivity of G_{12}, t is the time elapsed, G_{o12} is the initial in-plane shear modulus of the fibers, $\dot{\varepsilon}_{12}$ is the in-plane shear strain-rate, $\dot{\varepsilon}_o$ is a basic strain-rate with which the current strain-rates are compared and is accepted as the strain-rate of the static loading for a given working strain-rate range. A time integration of the strain rates is deemed necessary as they are not constant in impact simulations and also because the stress-strain relationship for the fibers is based on their secant stiffness and not the tangential stiffness.

2.3. Damage Evolution in Constituents

In the current model, damage growth is based on a Weibull distribution of strengths which is commonly associated with the strength of fibers. The evolution function for damage describing fiber breakage at time step $n + 1$, is expressed as follows:

$$d_1^{(n+1)} = \min\left\{1 - \exp\left[-\frac{1}{m_1 e}\left(\frac{E_1|\varepsilon_{11}|}{\sigma_{1t|c}}\right)^{m_1}\right],\ d_1^{(n)}\right\} \quad \text{..... (14)}$$

where, $t|c$ denotes tension or compression. When $\varepsilon_{11} > 0$, the parameters for tension are utilized otherwise the parameters provided for compression are used. When the damage d_1 reaches 0.01 in tension, the finite element is considered totally failed. $\sigma_{1t|c}$ is not simply the strength of the fibers but is a reduced value given by the relation:

$$\sigma_{1t|c} = \frac{X_{t|c}}{b_{t|c}} \quad \text{..... (15)}$$

where, $X_{t|c}$ is the tensile/compressive strength of the pure fibers, and $b_{t|c}$ is a reduction factor. The physical justification for using such a factor is the fact that fibers generally display reduced strengths in unidirectional composites as evidenced by the lower strength of the latter compared to the former in uni-axial longitudinal tension.

In the transverse directions, the damage evolution functions (equations 16 and 17) are considered to independent of the strain-rate. The properties of the fibers in both transverse directions are the same, therefore the evolution functions as well as their parameters are the same and only the history of the loading is different.

$$d_2^{(n+1)} = \min\left\{1 - \exp\left[-\frac{1}{m_1 e}\left(\frac{E_2|\varepsilon_{22}|}{\sigma_{2t|c}}\right)^{m_1}\right],\ d_2^{(n)}\right\} \quad \text{..... (16)}$$

$$d_3^{(n+1)} = \min\left\{1 - \exp\left[-\frac{1}{m_1 e}\left(\frac{E_2|\varepsilon_{33}|}{\sigma_{2t|c}}\right)^{m_1}\right],\ d_3^{(n)}\right\} \quad \text{..... (17)}$$

The damages in transverse directions of the fibers are constrained to not exceed 0.10.
Damages are imposed on the matrix material, but they affect only the shear stresses of the resin, which is considered to be the main contributor to the shear stresses of the RVC. A single Weibull distribution function is accepted again as an evolution function of the damages but it involves the ultimate strain for the damage development rather than the ultimate stress. The damage evolution function for in-plane shear is as follows:

$$d_4^{(n+1)} = \min\left\{1 - \exp\left[-\left(\frac{|\varepsilon_{12}|}{\varepsilon_{4m}}\right)^{m_s}\right],\ d_4^{(n)}\right\} \quad \text{..... (18)}$$

Strain-rate dependency is considered only for the ultimate strain, ε_{4m}, and the strain-rate sensitivity factor is the same as for the shear effect on the fiber breakage:

$$\varepsilon_{4m} = a_{s4} s_s + \varepsilon_{o4m} \quad \text{..... (19)}$$

The other damage evolution functions for the matrix material are not strain-rate dependent. These damages for time step $n + 1$ are calculated as follows:

$$d_5^{(n+1)} = \min\left\{1-\exp\left[-\left(\frac{|\varepsilon_{23}|}{\varepsilon_{5m}}\right)^{m_s}\right],\ d_5^{(n)}\right\} \qquad \text{..... (20)}$$

$$d_6^{(n+1)} = \min\left\{1-\exp\left[-\left(\frac{|\varepsilon_{31}|}{\varepsilon_{o4m}}\right)^{m_s}\right],\ d_6^{(n)}\right\} \qquad \text{..... (21)}$$

The damages of the matrix material are constrained to not exceed 0.20. These damages are applied on the matrix material shear stresses when the stress response of the sub-cells is calculated. The concept of the effective stress is accepted here for the matrix material, rather than the concept of the effective elastic moduli, because the matrix material model is isotropic while the damages in the material are not.

2.4. Delamination

Delamination is a failure mode which is due to the quadratic interaction between the through-the-thickness stresses of a lamina and is assumed to be mainly a matrix failure. The loading criterion for this failure mode has the following form:

$$S^2\left\{\left(\frac{E_3\langle\varepsilon_{33}\rangle}{S_{3t}}\right)^2+\left(\frac{G_{23}\gamma_{23}}{S_{230}+S_{SR}}\right)^2+\left(\frac{G_{31}\gamma_{31}}{S_{310}+S_{SR}}\right)^2\right\}-r^2=0 \qquad \text{..... (22)}$$

where $\langle\ \rangle$ are Macaulay brackets, E_3 is the normal tensile modulus of the lamina, G_{23} and G_{31} are the transverse shear moduli of the lamina, S_{3t} is the through-the-thickness tensile strength of the lamina, S_{230} and S_{310} are the transverse shear strengths of the lamina for tensile ε_{33}, r is the damage threshold, and S is a scale factor introduced to provide better correlation of delamination area with experiments which can be determined by fitting analytical prediction to experimental data for the delamination area. Under compressive through-the-thickness strain, $\varepsilon_{33}<0$, the damaged surface (delamination) is considered to be "closed", and the damage strengths are assumed to depend on the compressive normal strain ε_z similar to Coulomb-Mohr theory, i.e.,

$$S_{SR} = E_3 \tan\varphi\langle-\varepsilon_z\rangle \qquad \text{..... (23)}$$

where, φ is the Coulomb's friction angle. The normal tensile modulus of the lamina is computed at the first time step and stored as a material property.

$d_{lam}^{(n+1)}$ is the damage variable associated with this failure mode and its evolution is given by the relation:

$$d_{lam}^{(n+1)} = \min\left\{1-\exp\left[\frac{1}{m_d}\left(1-r^{m_d}\right)\right], d_{lam}^{n}\right\} \qquad \text{.... (24)}$$

where, r is the damage threshold as given in equation (22) and m_d is the damage exponent for delamination. Delamination damage is constrained at 0.10 to avoid numerical difficulties and when this maximum value is reached in an element, it is considered to be fully delaminated.

When delamination failure given by equation (22) occurs in an element, depending on the opening or closing of the damage surface, the damages variables ($d_z^{(n+1)}$, $d_{yz}^{(n+1)}$ and $d_{zx}^{(n+1)}$) specified in equations (25) and (26) are applied on the effective RVC stresses.

$$\text{For tensile mode, } \varepsilon_{33} > 0: \; d_z^{(n+1)}, d_{yz}^{(n+1)}, d_{zx}^{(n+1)} = d_{lam}^{(n+1)} \quad \text{….. (25)}$$

$$\text{For compressive mode, } \varepsilon_{33} < 0: \; d_{yz}^{(n+1)}, d_{zx}^{(n+1)} = d_{lam}^{(n+1)} \quad \text{….. (26)}$$

For tensile mode, all the through-the-thickness stress components σ_{33}, σ_{23} and σ_{31} of RVC are reduced while for compressive mode, the damage surface is considered to be closed, and thus, σ_{33} is assumed to be elastic and only σ_{23} and σ_{31} are reduced.

2.5. RVC Stress Calculations

The effective stresses in the RVC are determined from the sub-cell values in two phases: first, stresses in the fiber ***f*** and matrix $\boldsymbol{M_A}$ are used to determine the effective stresses of part ***A***; then these stresses and the stresses in matrix $\boldsymbol{M_B}$ are used to determine the effective stresses in the RVC.

As stated earlier, iso-strain boundary conditions are assumed for all the three sub-cells of the RVC. This implies the rule of mixture for the stress calculations. The simple rule of mixture applied on all components of the fiber and the matrix material stresses means physically that the fiber and matrix materials act in parallel in all directions under loading, which is definitely not realistic. However, this assumption is made in order to simplify the micro-mechanical relations. The direct stresses of part ***A*** are calculated from the direct stresses of the fiber sub-cell ***f*** and the matrix sub-cell $\boldsymbol{M_A}$ using the following relations:

$$\sigma_{11}^{A} = W_f \sigma_{11}^{f} + (1 - W_f)\sigma_{11}^{m_A} \quad \text{….. (27)}$$

$$\sigma_{22}^{A} = W_f \sigma_{22}^{f} + (1 - W_f)\sigma_{22}^{m_A} \quad \text{….. (28)}$$

$$\sigma_{33}^{A} = W_f \sigma_{33}^{f} + (1 - W_f)\sigma_{33}^{m_A} \quad \text{….. (29)}$$

The behavior of unidirectional composites under shear is dominated by the behavior of the matrix material. The contribution of the fibers to the shear stress is very low compared to the contribution of the matrix material. Hence, ad hoc volume fraction coefficients are implemented for shear and a rule of mixture involving them is applied. Then, the shear stress of part ***A*** is determined, applying the damages of the matrix material introduced in the previous section, as follows:

$$\sigma_{12}^{A} = V_{s4}\sigma_{12}^{f} + (1 - V_{s4})(1 - d_4)\sigma_{12}^{m_A} \quad \text{….. (30)}$$

$$\sigma_{23}^{A} = V_{s5}\sigma_{23}^{f} + (1 - V_{s5})(1 - d_5)\sigma_{23}^{m_A} \quad \text{….. (31)}$$

$$\sigma_{31}^{A} = V_{s4}\sigma_{31}^{f} + (1 - V_{s4})(1 - d_6)\sigma_{31}^{m_A} \quad \text{….. (32)}$$

The shear volume fraction coefficients, V_{s4} and V_{s5}, are different for the in-plane and transverse shear. They have values quite lower than the volume fraction of the fibers. Since the matrix material is modeled as viscoplastic and the fibers are modeled as elastic, after the saturation of the plasticity in the matrix material, the contribution of the fibers to the shear stress of the sub-cells plays a role of strain hardening.

Finally, the effective stresses in the RVC are obtained by applying the rule of mixtures again which yields the following relations including the softening of through-the-thickness components due to delamination failure as follows:

$$\begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{12} \\ \sigma_{23} \\ \sigma_{31} \end{Bmatrix}_{RVC} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ & 1 & 0 & 0 & 0 & 0 \\ & & d_z^{(n+1)} & 0 & 0 & 0 \\ & & & 1 & 0 & 0 \\ & symm & & & d_{yz}^{(n+1)} & 0 \\ & & & & & d_{zx}^{(n+1)} \end{bmatrix} \left(W_f \begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{12} \\ \sigma_{23} \\ \sigma_{31} \end{Bmatrix}_A + W_m \begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{12} \\ \sigma_{23} \\ \sigma_{31} \end{Bmatrix}_{M_B} \right) \quad \text{..... (33)}$$

The total strains of the RVC, the total stresses in the matrix material, the internal state variables of the matrix material, the damage variables, and the time average strain-rate logarithms, S_d and S_s, are kept as history variables at each time step of the explicit time integration process for the next time step calculations.

3. Damage Parameter Estimation

The damage parameter that has been used in the Weibull functions above (equations 14, 16, 17 etc.) has been observed to be very problem dependent and difficult to characterize. A small value of the damage exponent (for ex. m_1 in equation 14) makes the material behave in a very ductile manner and the behavior becomes increasingly brittle as this value increases. Hence, it is difficult to obtain the softening response of most quasi-brittle materials. The softening response heavily depends on the set-up and test machines, which can lead to very different results. The choice of damage parameters for each mode has been debated by Vaziri et al. [5] and Tabiei et al. [3]. A procedure for the calculation of softening parameter used in the damage evolution function has been discussed below.

In their work, Pinho et al. [6] have calculated the maximum strain ε^f, as a function of the energy per unit area of the surface created Γ, the material strength σ^0 and a one element dimension, L.

$$\varepsilon^f = \frac{2 * \Gamma}{\sigma^0 * L} \quad \text{..... (34)}$$

This maximum strain ε^f calculated above has been in turn used in the calculation of the damage variable.

$$d^{(n+1)} = \min\left\{ 1 - \varepsilon^f * \frac{(\varepsilon - \varepsilon^0)}{\varepsilon(\varepsilon^f - \varepsilon^0)}, d^n \right\} \quad \text{..... (35)}$$

Now, apart from the function itself this formulation of damage is similar to what we have used above in section (2.3). Hence, the area under the damage functions can be been equated (equations (35) and (20)) and we can iteratively solve for the damage parameter by minimizing the error. As a preliminary test, this concept has been implemented in MATLAB® for both the damage functions mentioned above for a wide range of element lengths and the results can be observed in figure 2 below. Each curve on the right in figure 2 represents the damage parameter calculated for a specified element length and it can be clearly seen that the damage curves look identical in both the figures.

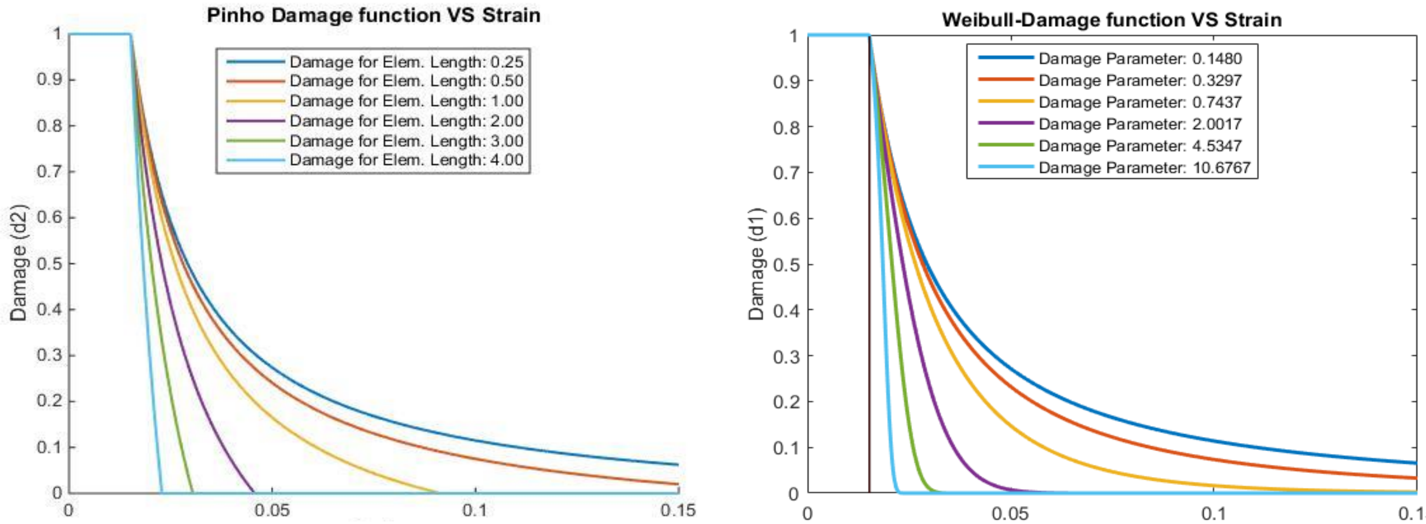

Figure (2): Damage function comparision after iteratively solving for the damage parameter.

4. Numerical Result and Discussion of Inter-laminar delamination

As a verification example, an impact event on CFRP plates made of T800H/3900-2 fiber/resin system with a laminate stacking sequence of $[45/90/-45/0]_{3S}$ and total thickness of 4.65 mm is simulated using the current material model in LS-DYNA. These experimental results were originally obtained by an extensive investigation of out-of-plane impact loading of composite test coupons by Delfosse (8) and were used by Williams and Vaziri et al. [2] to evaluate the predictive capability of a plane-stress CDM based model for composite materials that they implemented in LS-DYNA.

The goal of this study is to predict the delamination measurement made by the experiments and reported in Williams et al [2]. The test coupon consists of a simply supported 76.2 mm by 127 mm plate impacted by a hemispherical steel impactor ($25.4\,mm$ in diameter), which in the numerical computation is treated as rigid body. The FE model is shown in figure 3.

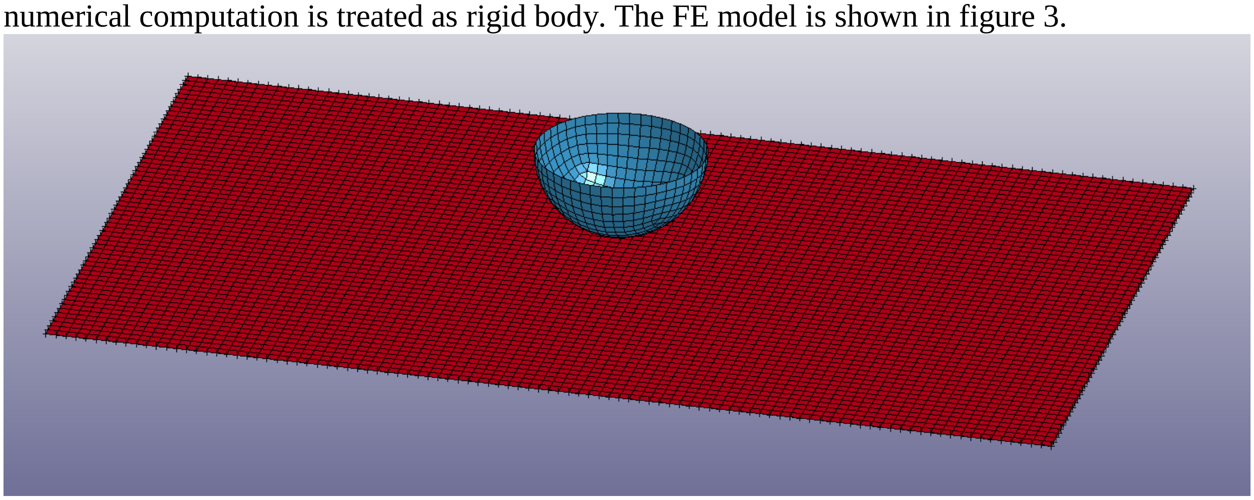

Figure (3): A full model view of the T800H/3900-2 CFRP laminate

The CFRP plate in itself consists of 24-thru thickness integration points with each integration point representing a layer of the laminate stacking sequence $[45/90/-45/0]_{3S}$.

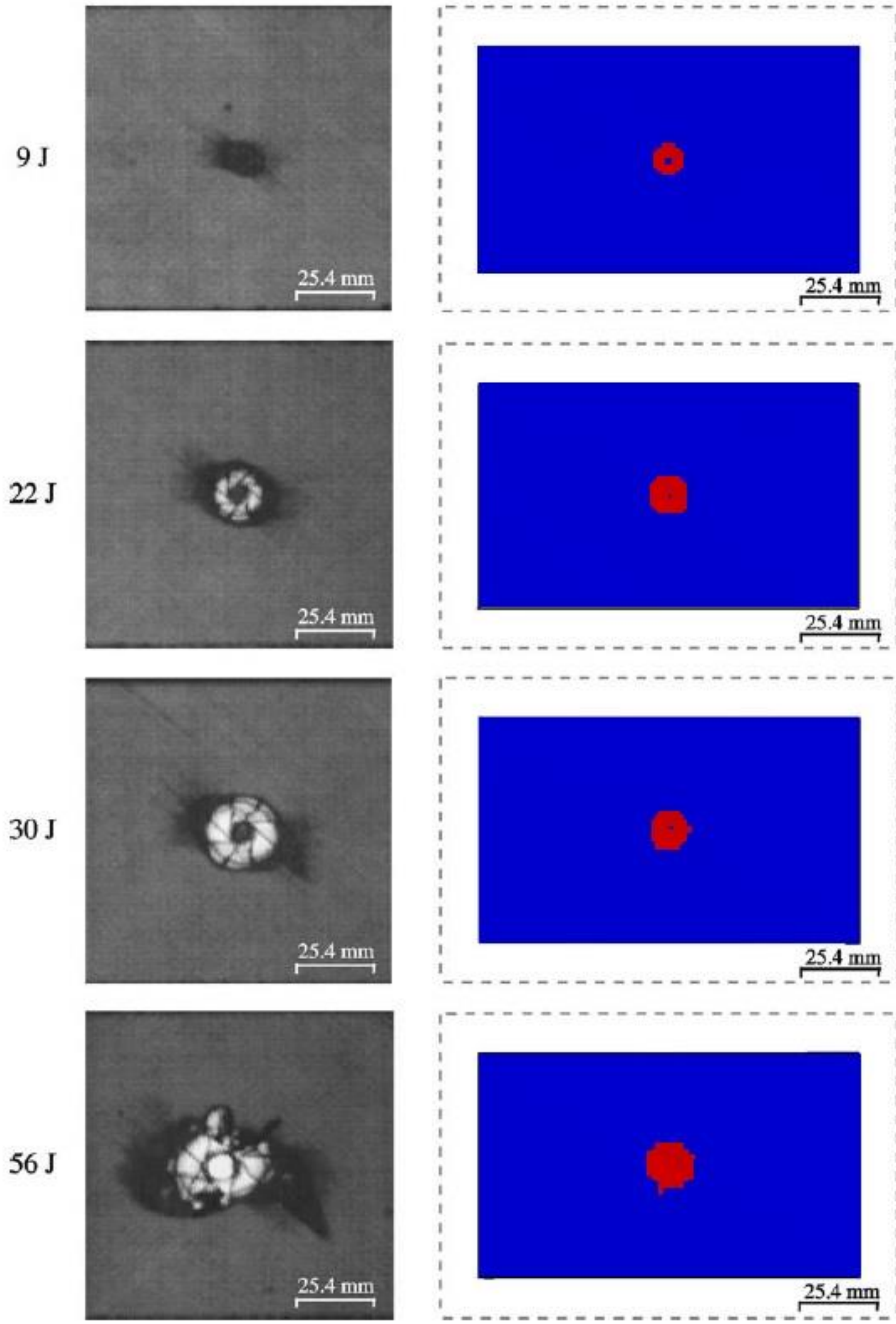

Figure (4): Comparison of the delamination damage and experimental C-scan images on a T800H/3900-2 CFRP plate. Numerical results obtained using Shell-25 element formulation in LS-DYNA.

Figure 4 qualitatively compares the predictions of projected inter-laminar delamination to the C-scan images of delamination growth for the low mass impact events provided in [2]. It is to be noted that the numerical results predicted in Figure 4 use the thickness-stretch shell element formulation .i.e., ELFORM=25. The box drawn around the numerical results highlights the location of the plate boundaries relative to the part of the plate modelled.

The same set of tests have been carried out with the standard shell elements i.e., ELFORM=2 in LSDYNA and the results can be observed in Figure 5.

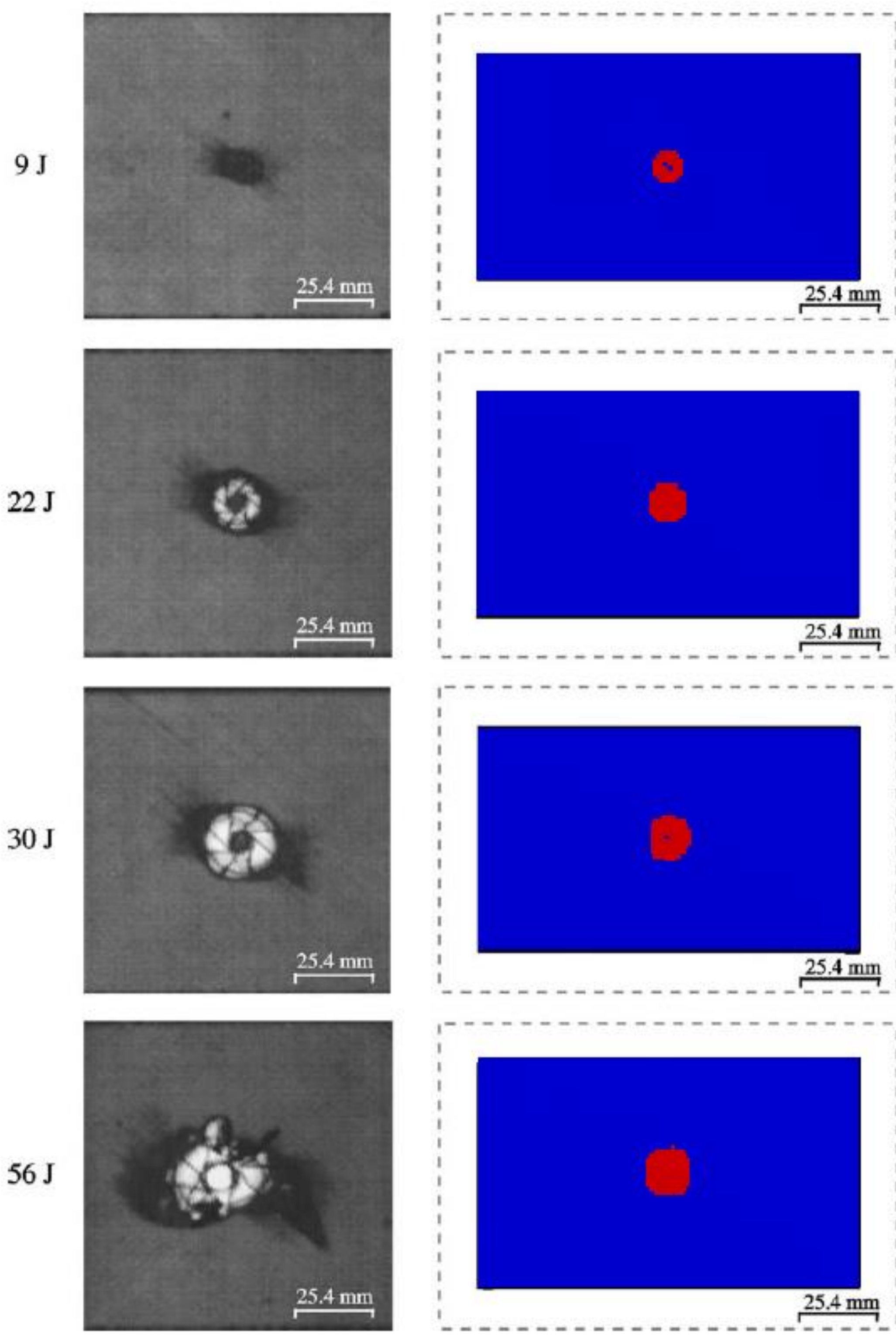

Figure (5): Comparison of the delamination damage and experimental C-scan images on a T800H/3900-2 CFRP plate. Numerical results obtained using Shell-2 element formulation in LS-DYNA.

Observing the results presented in Figures 4 and 5, the following comments can be made:

a) The total delamination area looks smaller as compared to the experiments when both sets of images in each figure (numerical and C-scan) are set to the same scale.
b) The shape of the delamination however looks quite identical in both the cases as compared to the experiments.
c) It can be said that the delamination behavior's when using ELFORM=2 or 25 is identical.

However, in order to understand the effect of Z-Stress on delamination behavior it is important to consider the effect of each term on the left hand side of equation (22). In this equation, the first term accounts for the contributions from Z-Stresses, the second term for the YZ-Stresses and the last term for the ZX-Stresses of the lamina. Further, a single element inside the delamination zone has been selected for the models run with different element types (ELFORM=2 and ELFORM=25) and the contribution of each individual term in equation (22) has been analyzed. The results of which are shown in Figures 6 and 7.
The following comments can be made on the results presented in Figures 6 and 7.

a) A contribution of the Z-Stresses is seen in the model run using Shell ELFORM=25, however this is significantly small compared to the contribution from the YZ-Stresses. It is to be noted that as the total value of these terms goes beyond a value of 1, damage is introduced into the model and the load bearing capacity of the lamina in Z, YZ and ZX direction is reduced.
b) As expected for the model run with Shell ELFORM=2, the Z-Stress contribution is zero and the total damage is dominated by the YZ-Stress contributions in the delamination criteria.
c) The smaller contribution of the Z-Stresses in predicting delamination explains why we observe near identical results for the results presented in figures 4 and 5.

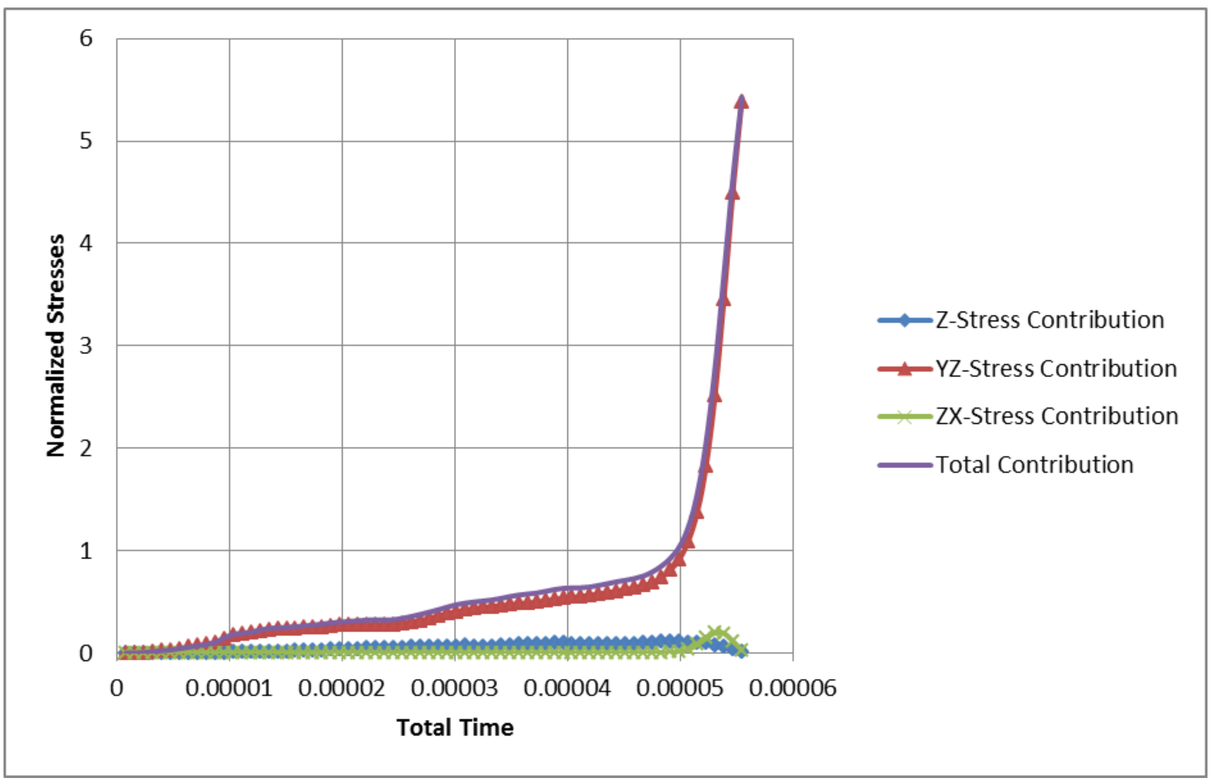

Figure (6): Effect of each term in the calculation of delamination, Model run with Shell ELFORM = 25

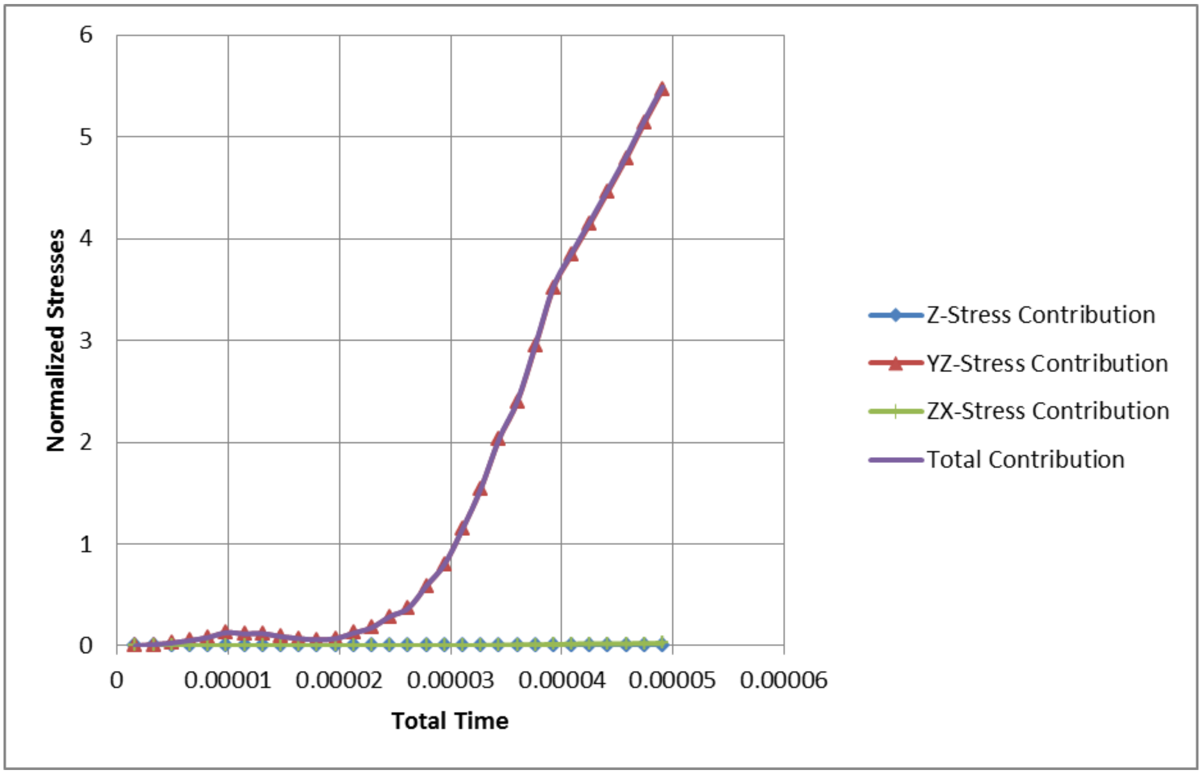

Figure (7): Effect of each term in the calculation of delamination, Model run with Shell ELFORM = 2

5. Conclusions

In the current work, using LS-DYNA and a micro-mechanical material model [3] a qualitative delamination study has been performed for impact events with various normal incident energy levels (9.4J, 22J, 33.4J and 56.4J) on CFRP plates made of T800H/3900-2 fiber/resin system. These analyses have been carried out using shell element formulations 2 (which uses a plane-stress formulation) and 25 (which requires a full 3D constitutive model), primarily to study the effect of Z-Stresses in the delamination prediction. The results indicate that despite a smaller effect of Z-Stresses in the overall delamination prediction, the contribution resulting from this term cannot be ignored and hence it can be said that the thickness-stretch formulations (Shell ELFORM=25) can be considered more reliable in predicting delamination in composites. Though not completely accurate, both the element formulations have been able to predict quite realistic delamination results for impact simulations considered.

In addition, a physically quantifiable method of determining the damage parameters based on the energy per unit area of the surface created has been presented. A 1-D case demonstrating the procedure has been implemented in MATLAB and has been found to be viable. As a future aspect of this work it is intended to implement this procedure into the micro-mechanical material model and enhance its capability.

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