Numerical Modeling of Woven Carbon Composite Failure

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Abstract

This paper presents application of a MLT-based (Matzenmiller, Lubliner, Taylor) approach to model damage in woven carbon composite materials. The MLT formulation has been adapted to shell elements to model individual composite plies. The implementation of the model is discussed along with simple test cases to demonstrate the material response and limitations within the original MLT model. One of these limitations has been addressed through implementation of different damage parameters for tensile and compressive loading. In addition, this damage-based approach has been modified by the use of a non-local damage treatment to distribute accumulated damage across element boundaries. Application of this model to simple test cases indicates that the model demonstrates expected behaviour.

Introduction

Numerical modeling of damage in composite structures is of significant interest as these materials are now commonly used for structural and energy absorption applications. However, the constitutive description of these materials is not trivial due to the various damage mechanisms which contribute to the material response. A model based on the continuum damage mechanics (CDM) approach first proposed by Matzenmiller et al. (1995) to describe the accumulation of damage in composite materials has been considered. Several authors have investigated this approach. In particular, Williams et al. (2000) thoroughly discusses the origins of CDM and its application to numerical analysis of composite materials, including the MLT (Matzenmiller, Lubliner, Taylor) approach. A version of this model was previously implemented in LS-Dyna as a user material model for solid elements, and was successful in the simulation of ballistic composite response and damage to impact (van Hoof, 1999, Gower, 2003). In this situation, the transverse or through-thickness response of the material is important and requires the use of solid elements. This level of detail is acceptable when the area of interest within the composite is small. However, when considering real structures, such as composite crush structures for energy absorption, this level of detail is not feasible and more computationally efficient shell elements must be considered. It is important to note that the level of detail within the finite element model must also be represented in the constitutive model. For example, the use of multiple solid elements through the thickness of each composite ply allows for a model to describe response and damage at the sub-ply level. In contrast, a single shell element could be used to represent multiple composite plies. In practice it has been found that the former is computationally too expensive and the latter overly simplifies the complex material response of a damaged composite. As such, an implementation of the MLT approach for a shell element representing a single composite ply has been undertaken. It is anticipated that delamination in the composite will be modeled through ties between adjacent plies.

Constitutive Model Implementation for Shell Elements

The MLT damage approach is based on the premise that damage is accumulated within a material based on deformation and loading in various directions. In the case of shell elements, the damage is calculated in the longitudinal (tensile/compressive), transverse (tensile/compressive), and in-plane shear directions. Van Hoof et al. (1999) developed equations (1) and (2) based on the work of Matzenmiller et al. (1995) and Williams et. al. (1995) to describe the onset of damage for a particular damage mode. The subscript 'i' corresponds to the loading direction (1 = longitudinal, 2 = transverse, and 4 = in-plane shear). It is important to note that the damage threshold 'f_i' is calculated in the current time step (t) while 'r_i' is calculated in the previous time step (t-Δt).

$$f_i = \left[\frac{\varepsilon_i}{\varepsilon_{failure,i}}\right]^{m_i} - r_{i_{t-\Delta t}} \quad (1)$$

$$r_{i_{t-\Delta t}} = \left[\frac{\varepsilon_i}{\varepsilon_{failure,i}}\right]^{m_i} \quad (2)$$

When the damage threshold (f_i) of an element is greater than zero, the element begins to accumulate damage. The damage accumulation rate of the element for a particular damage mode is given by equations (3) and (4) below, also developed by Matzenmiller et al. (1995) and later implemented by van Hoof et al. (1999).

$$g_i = \frac{(1-\omega_i)}{e}\left[\frac{\varepsilon_{rate,i}}{\varepsilon_{Failure,i}}\right]\left[\frac{\varepsilon_i}{\varepsilon_{Failure,i}}\right]^{(m_i-1)} \quad (3)$$

$$\begin{aligned} \omega_1 &= (g_1 + g_4)(\Delta t) \textit{ (longitudinal)} \\ \omega_2 &= (g_2 + g_4)(\Delta t) \textit{ (transverse)} \\ \omega_4 &= (g_1 + g_2 + g_4)(\Delta t) \textit{ (in-plane shear)} \end{aligned} \quad (4)$$

The coupling of damage in the longitudinal, transverse, and in-plane shear directions is evident in equation (4). In this manner, an element undergoing longitudinal strain will accumulate damage in both the 1- (ω_1) and 4-directions (ω_4). It is important to note that in equations (1) to (4) damage is treated identically in the longitudinal and transverse directions, for the purposes of simulating a woven composite laminate. This treatment differs from that used previously by Matzenmiller et al. (1995) and Williams et al. (2000) in which longitudinal damage was not coupled with any other damage modes, and transverse damage was coupled with shear damage.

The representative damage variables, ω_i, are then used to reduce the material stiffness in the corresponding directions. Equation (5), first proposed by Matzenmiller et al. (1995) and later implemented by Williams et al. (1995) and van Hoof et al. (1999) for solid elements, defines the reduced stiffness matrix for a shell element and shows that the element stiffness is predicted by the conventional elastic constants scaled by the damage variables.

$$\begin{bmatrix}\sigma_1\\ \sigma_2\\ \tau_{12}\end{bmatrix}=\frac{1}{D}\begin{bmatrix}(1-\omega_1)E_1 & (1-\omega_1)(1-\omega_2)\nu_{12}E_2 & 0\\ (1-\omega_1)(1-\omega_2)\nu_{21}E_1 & (1-\omega_2)E_2 & 0\\ 0 & 0 & (1-\omega_4)G_{12}\end{bmatrix}\begin{bmatrix}\varepsilon_1\\ \varepsilon_2\\ \gamma_{12}\end{bmatrix} \quad (5)$$

where

$$\frac{-\nu_{21}}{E_2}=\frac{-\nu_{12}}{E_1}$$

$$D=1-(1-\omega_1)(1-\omega_2)\nu_{12}\nu_{21}>0$$

Equations (1) through (5) detail the manner in which an element accumulates damage and undergoes a reduction in stiffness. The rate at which damage accumulates (and the rate at which stiffness is degraded) is thus a function of the material parameters (most notably the failure strains) and the exponents m_i.

Effect of the Damage Exponent m

In general, the material parameters required to describe a composite are available from various publications, including material data published by the manufacturers for various fibre/matrix combinations. This includes modulus, failure strength and Poisson's ratio. However, determination of the damage exponents m_i requires more attention.

The effect of the exponent m on the stress-strain response of an element is shown in Figure 1. This exponent determines the brittle/ductile response of the element. High values of m cause a stress-strain response similar to a brittle material, with little or no loss in stiffness prior to failure and full damage corresponding to zero stiffness shortly after failure. Low values of m describe a material that absorbs more energy prior to complete damage, with significant stiffness degradation prior to failure and a more gradual loss of stiffness after failure.

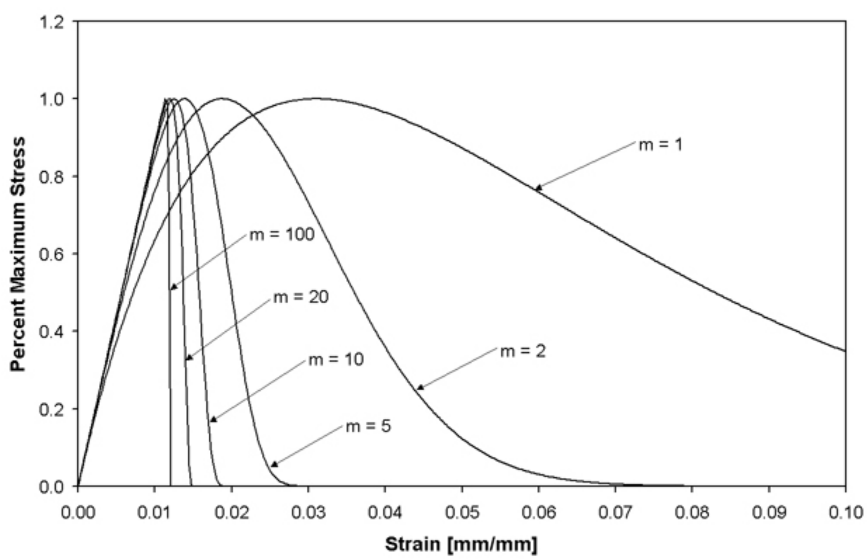

Figure 1: The effect of the exponent *m*

As discussed by Williams et al. (2000) the selection of *m* is difficult as it has been found to be a function of the material, loading rate, and element size. These are common issues when considering damage-based constitutive models and are addressed in more detail below. In studies of ballistic impact on woven Kevlar composites, van Hoof et al. (1999) found that an exponent value of $m = 8$ provided a reasonable prediction of the material stress-strain response. Specifically, this value of m resulted in relatively brittle behaviour (Figure 1), which represented the material considered at high rates of strain. In similar studies of impact on unidirectional CFRP laminates, Williams et al. (2000) achieved good correlation with experimental results at low to medium impact energy using an exponent value of $m = 10$. In the same study it was also found that at higher impact energies an exponent value of $m = 20$ provided better correlation than a value of 10, highlighting the dependence of *m* on the loading rate.

Constitutive Model Implementation

The material model outlined above has been implemented into a FE code as a user-defined material model in LS-DYNA v. 970. The following section outlines the model and the predicted results. Examples of the model performance are provided using a simple single element test case.

Definition of Material Properties

The material parameters that define the behaviour of the material are shown in Table 1. These properties correspond to published values for a common 2x2 twill-weave pre-impregnated carbon/epoxy fabric. In this case, the failure strains required for equations (1) to (4) were calculated from the strengths listed below. The damage exponents specified can be different in each material direction (local 1, 2, or 4), but were set equal to 10 for the initial studies following the recommendations of Williams et al. (2000) and van Hoof et al. (1999).

Table 1: Input parameters for ACG CFS003/LTM25 for shell elements. [Cruz et al., 1996]

Parameter Symbol	Value	Description
E_1	48. 7 GPa	Modulus of elasticity in the longitudinal (local 1) direction.
E_2	51.8 GPa	Modulus of elasticity in the transverse (local 2) direction.
G_{12}	2.85 GPa	Modulus of elasticity in the shear (local 4) direction.
ν_{12}	0.042	Poisson’s ratio.
σ_{f1t}	562.6 MPa	Tensile strength in the longitudinal (local 1) direction.
σ_{f1c}	641.9 MPa	Compressive strength in the longitudinal (local 1) direction.
σ_{f2t}	612.3 MPa	Tensile strength in the transverse (local 2) direction.
σ_{f2c}	563.3 Mpa	Compressive strength in the transverse (local 2) direction.
τ_{12}	84.12 MPa	Shear strength in the in-plane (local 4) direction
m_1	10	Damage exponent in the longitudinal (local 1) direction
m_2	10	Damage exponent in the transverse (local 2) direction
m_4	10	Damage exponent in the in-plane (local 4) direction

Constitutive Model Response

A single element was used to verify the behaviour of the user-defined material model. The predicted stress/strain and damage/strain curves of the element subjected to monotonic tension and compression (separately) are shown in Figure 2. It is evident that damage rapidly accumulates after approximately 1% strain, and softening of the material is evident at slightly higher strains. It is important to note the different failure stresses (and strains) in tension and compression corresponding to the values in Table 1. The equivalence of the damage variables ω_1 and ω_4 is a consequence of equation (4). The behaviour of the 1-element model matches the expected response from the constitutive equations for uniaxial tension and compression.

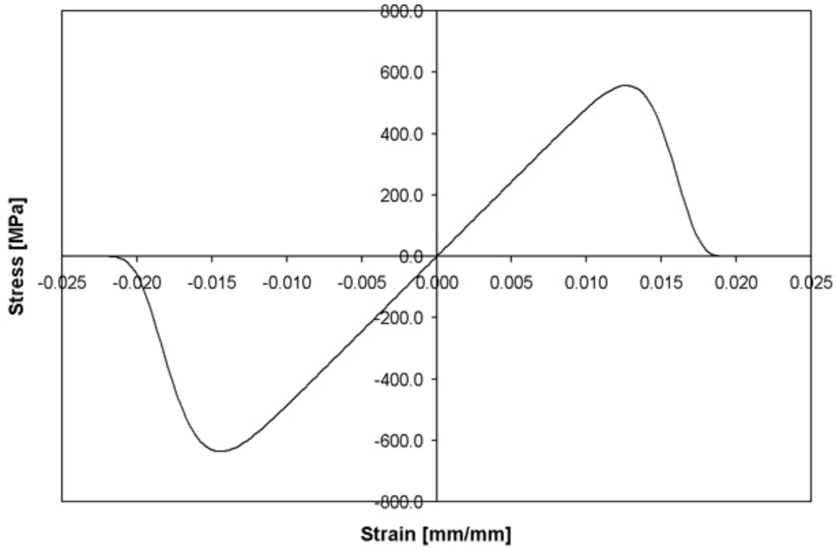

Figure 2a: Stress vs. strain output of 1-element model with exponent *m* = 10.

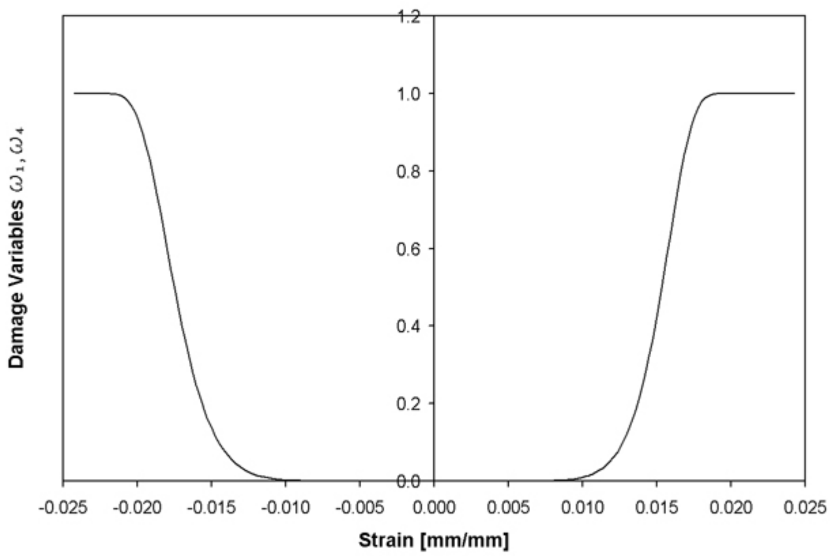

Figure 2b: Damage vs. strain output of 1-element model with exponent *m* = 10.

Limitations of the MLT Constitutive Model

The most significant limitation of the MLT constitutive model is the coupling of initial modulus with post-failure deformation. The use of a high value for the exponent *m* provides an essentially linear elastic material that fails in a brittle manner, with little or no post-failure stiffness (Figure 1, *m* = 100). In this case, the initial modulus of the material is accurately represented, but no allowance exists to incorporate post-failure load-carrying capability. A low value of the exponent *m* represents a more ductile response that may undergo significant deformation after the onset of damage while still sustaining load. However, the elastic modulus deviates grossly from the input modulus prior to failure (Figure 1, *m* = 1).

A related issue is the use of identical values of the exponent *m* for tensile and compressive calculations. As shown in Figure 2, the material response is essentially identical in tension and compression (with the exception of failure stress and strain). For many composite materials such a response is not realistic.

A third issue with the MLT approach is related to unloading of the material. Some examples of the stress/strain response to a partial load (and subsequent removal of load) are shown in Figure 3. Prior to the accumulation of damage, the model may be loaded and unloaded elastically. However, once damage has been generated in the model, the element will unload linearly (at the reduced stiffness) along a line that intersects the origin on a stress vs. strain diagram. Due to this behaviour, the model cannot accurately predict the permanent deformation of a 'partially damaged' composite material. This is an issue if unloading of the material is encountered and if this unloading contributes to the overall response of the structure. However, in many impact situations, the deformation is monotonic and increasing such that the unloading phase does not affect the general response of the model.

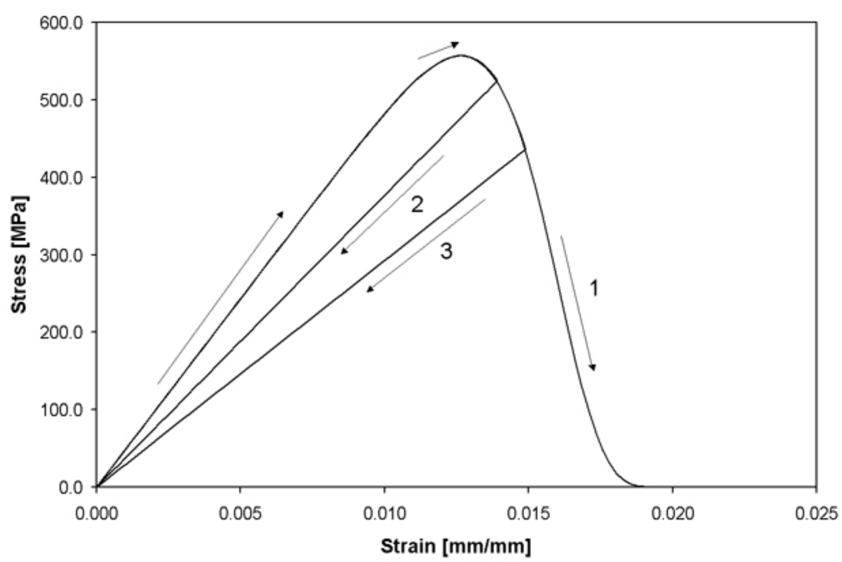

Figure 3: Stress vs. strain output of 1-element model showing (1) monotonic tension and (2,3) partial tension and subsequent unloading.

Finally, although it is not evident in the presented 1-element model, localization of damage is a known problem associated with most CDM approaches. As discussed by Williams et al. (2000), localization of damage leads to a dependence of the numerical solution on the mesh density, usually without convergence to a unique solution. This is an important aspect from a numerical modeling perspective since there is a desire to minimize computation time by maximizing element size. Further, real structures are necessarily complicated in geometry, which leads to non-uniform element size in various regions.

While the coupling of pre- and post-failure response and reduced unloading stiffness are fundamental characteristics of the constitutive model, some of the issues with the MLT model can be addressed directly. The focus of the current research is to address the limitations in the original MLT model and improve this model for application to predict the response and damage of composite structures.

Asymmetric Tensile and Compressive Behaviour

It is well known that, at a ply level, the tensile and compressive damage response of a material may differ. This leads to the need for asymmetric (in tension and compression) values of the exponent m, which has been incorporated into the constitutive description. An example of the modified model is shown in Figure 4. In this case, the exponent $m = 10$ in tensile loading while in compressive loading $m = 5$. In this manner any combination of exponents could be used to better characterize the behaviour of a given material.

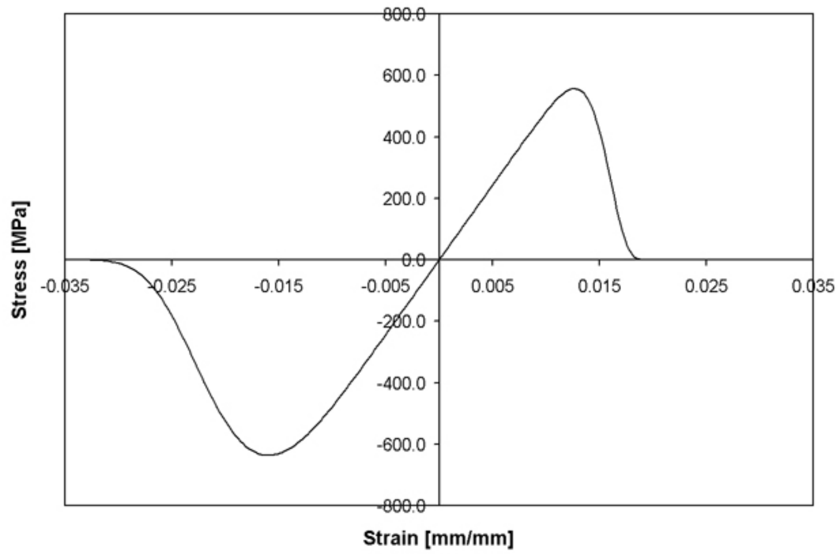

Figure 4: Stress vs. strain response of 1-element model using asymmetric values of the exponent m.

Non-Local Damage Distribution

As indicated above, damage-based models have an inherent element size dependency. This is important from a practical standpoint since it requires a finite element mesh of constant size be used to model a component. Theoretically, this also implies that fictitious boundaries (element edges) exist which contain or confine the material damage. In order to reduce the effects of localization of damage (and mesh dependency), a non-local damage distribution function has been implemented with the composite model. The function, *MAT_NONLOCAL in LS-DYNA

v. 970 has been used to distribute the material damage over a representative volume of material, specified by the user. Although this method is meant to be applied to elements with sizes approaching the length scale of the material (e.g. material grain size in metals, or repeating unit cell size in woven composites), it can also be used practically at larger element sizes to reduce mesh size dependency. A detailed description of the equations and typical parameter values can be found in the LS-DYNA Keyword User's Manual (2003). In the current model the non-local treatment is applied to the damage variables ω_i and the primary input of interest is the radius, *L*, which defines the area over which the function is applied.

A two-element model can be used to illustrate the effect of the non-local treatment, shown in Figure 5. The displacement of all nodes is prescribed to create a sub-failure strain in the lower element and a super-failure strain in the upper element, and to prevent any interaction of the strains that might affect the accumulation of damage.

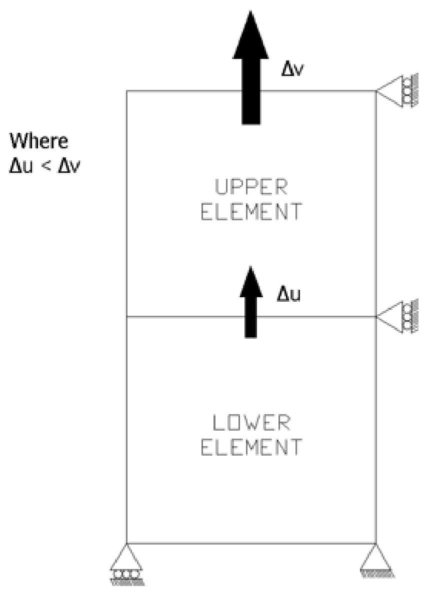

Figure 5: Schematic diagram of 2-element model.

Figure 6 shows the damage in the 1 (longitudinal) and 2 (transverse) directions without the use of non-local damage treatment. Figure 7 shows the same results with non-local damage treatment enabled, using a value of *L* such that the ratio $L/L_e = 1$ (where L_e = element length). In both cases the shear damage is not shown, as it is identical to the longitudinal damage due to the damage coupling described previously. Comparing Figures 6 and 7, it can be seen that damage is distributed from the upper element to the lower element in all directions, reducing the effect of element boundaries within the finite element mesh. Note that the increased damage in the longitudinal direction (and the resultant reduction in stiffness) causes a reduction in the Poisson's contraction of the element, which leads to a reduction of the transverse strain and damage.

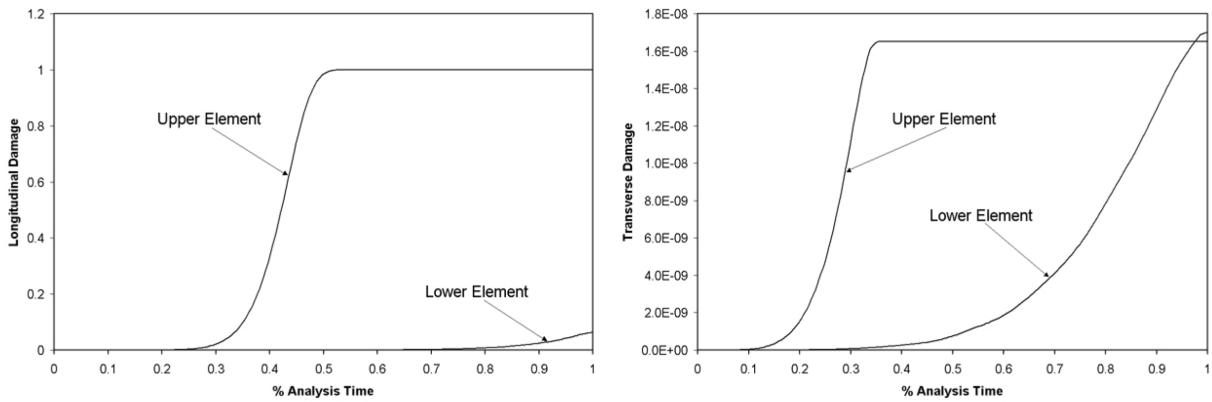

Figure 6: Damage vs. time for 2-element analysis without non-local damage treatment.

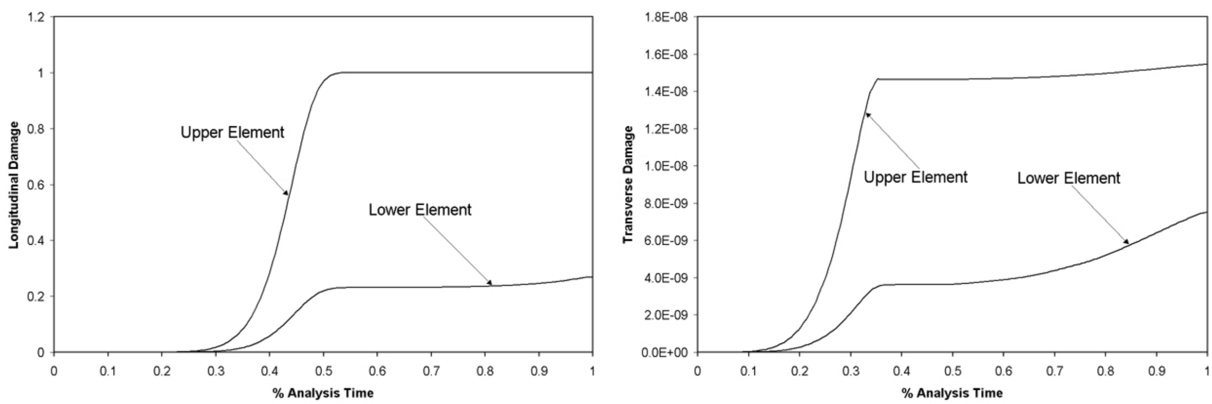

Figure 7: Damage vs. time for 2-element analysis with non-local damage treatment (L/L_e=1).

Summary

The constitutive model first proposed by Matzenmiller, Lubliner, and Taylor has been adapted to a shell formulation and implemented into LS-DYNA as a user-defined material model. The main limitations of the constitutive model are the coupling of pre- and post-failure response, the coupling of tensile and compressive properties, the elastic unloading of the material following partial damage, and the mesh sensitivity cause by the tendency for localization of damage. Through modification of the constitutive relationship, a modified composite model allows for the use of separate damage exponents m_i in tension and compression, effectively de-coupling these responses. In addition, the use of non-local damage treatments available within LS-DYNA provides a means of reducing mesh sensitivity.

Acknowledgements

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