A Multiscale Nonlocal Progressive Damage Model for Composite Materials

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In this paper, the advantages of a nonlocal progressive damage formulation are described and demonstrated. An approximation of the nonlocal formulation was implemented coupled with the MAT162 composite damage model as a User defined material model in the LS DYNA environment. A comparison of the local model and the nonlocal model is simulated for an 8-ply laminate under tension is carried for increasing mesh densities. The results show the regularization achieved by nonlocal models by providing mesh independent results.

I.   Introduction

Emerging Progressive Damage and Failure Analysis (PDFA) methods have the ability to predict ply-by-ply damage in composite materials. While many of these techniques have been demonstrated at the coupon level, there are still many structural applications where this type of analysis could be beneficial including fan blade out events and fuselage shielding applications. The NASA Advanced Composite Consortium (ACC) High Energy Dynamic Impact (HEDI) team seeks to develop these methods to have broad applicability across structural length scales from coupons, to elements, to subcomponents with a capstone validation article of a representative one- eighth fuselage structure [1], [2]. The candidate PDFA methods of LS-DYNA MAT162 [3], MAT261 [4], and Peridynamics EMU generally represent damage at the lamina level length scale. This length scale can result in steep computational costs and highly mesh dependent results when considering complex structures. When considering the question of what is required to scale these analysis methods to a structural problem, one must find a balance between computational efficiency and model fidelity.

In a local framework, strain softening due to damage results in strain localization and highly mesh dependent results because of the inherent localization. This is greatly dependent on the mesh discretization, which can lead to a loss of accuracy due to the fact that as a mesh gets refined, the dissipative variables get unrealistically concentrated into the smaller elements [5]. To overcome this issue, the nonlocal theory has been implemented.

Non-local continuum theory [6] is an integrated approach that accounts for characteristic length scale effects where the stress at a material point is a function of strain within a finite volume surrounding that point through a non-local kernel. The non-local approach, in general, also serves to homogenize and bridge length scales. Thus, the integral nonlocal enhancement converts the constitutive behavior from a local phenomenon to the integral average of all the elements within a preset radius of influence [7]. This approach provides a computationally efficient, mesh independent results.

The nonlocal algorithm requires the concurrent access to data from all integration points at each time step, which is not a common feature in most commercially available finite element software. Thus, an approximation of the nonlocal theory based on the formulation proposed by Tvergaard and Needleman [8] and extended by Andrade et al [9] was employed.   This nonlocal approximation makes use of a nonlocal factor calculated from the previous increment to determine the current approximate nonlocal value. This approximation however, requires the use of a small time step to maintain stability and is therefore apt for an explicit framework.

The overall aim of this research is to adopt a sub-laminate homogenization approach typically used for computational efficiency. In the sub-laminate approach, a group of laminates within the structure is bundled to which the homogenization is applied to bridge ply-scale to the sub-laminate scale. Non-local interactions arise when there is a strain gradient present at the sub-laminate scale. Therefore, the sub-laminate constitutive behavior is to be linked to the ply-scale through a non-local homogenization model. The non-local kernel is constructed from the stress-strain and damage relations of the 3D ply-scale models. The non-local approach also serves to regularize the mesh sensitivity

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associated with damage induced strain localization within a local framework. This provides a computationally efficient yet accurate enough approach to capture the effective response of the structural-scale behavior. Previously, a non-local progressive damage model was implemented as a user material subroutine in LS-DYNA. The non-local capability was added to the MAT162 model where non-local averaged strains are used in stress updates. Two simple single layer test cases were analyzed to validate the nonlocal model [10]. In the current work, this approach is utilized to analyze an 8-ply laminate under tension to demonstrate the advantages of the nonlocal effect.

II. Nonlocal Theory

In the 1970s and 1980s, Eringen [11] and Bazant [12] pioneered the development of nonlocal models for plasticity and damage. This was due to the need for capturing material heterogeneity and size effects and achieving convergent results [13]. More recently, Silling [14] demonstrated the nonlocality in heterogeneous materials and developed a peridynamic material model, Zobeiry et al [15] outlined calibrating the intrinsic length using DIC, CODAM2 a nonlocal sublaminate based continuum damage model was developed at the University of British Columbia and is available as MAT219 is LS-DYNA [16].

While classical continuum models do not allow intrinsic size dependence, molecular dynamics beyond a few nanometers is computationally very expensive. Nonlocal continuum theory is an integrated approach that accounts for characteristic length scale effects where the stress at a material point is a function of strain within a finite volume surrounding that point through a non-local kernel. The non-local governing equations are:

$$\sigma_{ij,j} = \rho \ddot{u}_i, \quad \sigma_{ij}(x) = \int_V \alpha(|x' - x|) C_{ijkl} \varepsilon_{kl}(x') dV(x'), \quad \varepsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i}) \quad (1)$$

where σ_{ij} is the stress tensor, C_{ijkl} is the elastic modulus tensor, ε_{ij} is the strain tensor, u_i is the displacement vector and $\alpha(|x' - x|)$ is the non-local kernel function of Euclidean distance $|x' - x|$. The nonlocal stress gradient theory $(1 - \ell^2 \nabla^2)\sigma_{ij} = C_{ijkl} \varepsilon_{kl}$ can be derived with a kernel function of the form $\alpha(|x' - x|) = (2\pi \ell^2)^{-1} K_0(|x' - x|/\ell)$ where K0 is the modified Bessel function and ℓ is the nonlocal internal length scale parameter. The properties of the kernel are such that it reverts to the Dirac delta function in the limit of vanishing internal characteristic length leading to classical elasticity.

Whenever a material accumulates damage, in the local framework as the hardening modulus becomes negative and the partial differential equations that govern the problem become ill posed [13]. This leads to mesh sensitive results as the partial differential equations are not unique. Numerically the results tend to get unrealistically localized into the smaller elements [9]. In the nonlocal framework, the results are mesh independent and converge to a unique solution. The nonlocal formulation also reduces the mesh orientation bias whereas in a local framework the damage follows the element mesh direction.

A detailed approach to the implementation of the nonlocal MAT162 model is described in our previous work [10]. The nonlocal approach in the current study is carried out in a 2D formulation where each ply is considered separately for the nonlocal averaging.

III. Analysis

An 8-ply [0, 90, +45, -45]$_s$ laminate loaded under uniaxial tension is simulated with the local and nonlocal model to demonstrate the advantages of the nonlocal approach. Three different mesh sizes are simulated for this problem. The nonlocal approach requires one addition material property, the intrinsic length (l_r) to be passed to the subroutine. The intrinsic length or the nonlocal radius is arbitrarily selected to demonstrate the nonlocal approach.

The geometry of the laminate is shown in Fig. 1 and IM7/855-2 is selected as the material with the properties listed in Table 1 [17]. A prescribed motion displacement boundary condition is defined at both the left and right ends. Three meshes of the same model are tested with increasing mesh densities. The meshes have 1800 (Mesh 1), 7200 (Mesh 2) and 28800 (Mesh 3) elements respectively. The size of the biggest element in Mesh 1- the coarsest mesh, is 5 mm. Therefore, the intrinsic length l_r is selected as 6 mm and is kept the same for all the meshes.
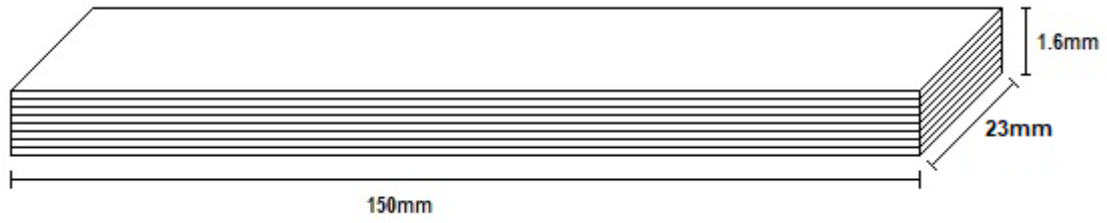
Fig. 1 Geometry of the laminate.

Table 1   Material properties of IM7/855-2 composite in GPa

E_a	E_b	E_c	G_{ab}	G_{bc}	G_{ca}	v_{ba}	v_{ca}	v_{cb}	X_T	X_C	Y_T	Y_c	S_{ab}
153	9.45	9.93	4.55	5.03	4.55	0.019	0.019	0.353	2.72	1.73	.094	.094	.0845

S_{bc}	S_{ca}	OMGMX	ECRSH	EEXPN	ELIMIT	AM1	AM2	AM3	AM4
0.0574	0.0845	0.999	0.1	2	0.3	100	10	1	1
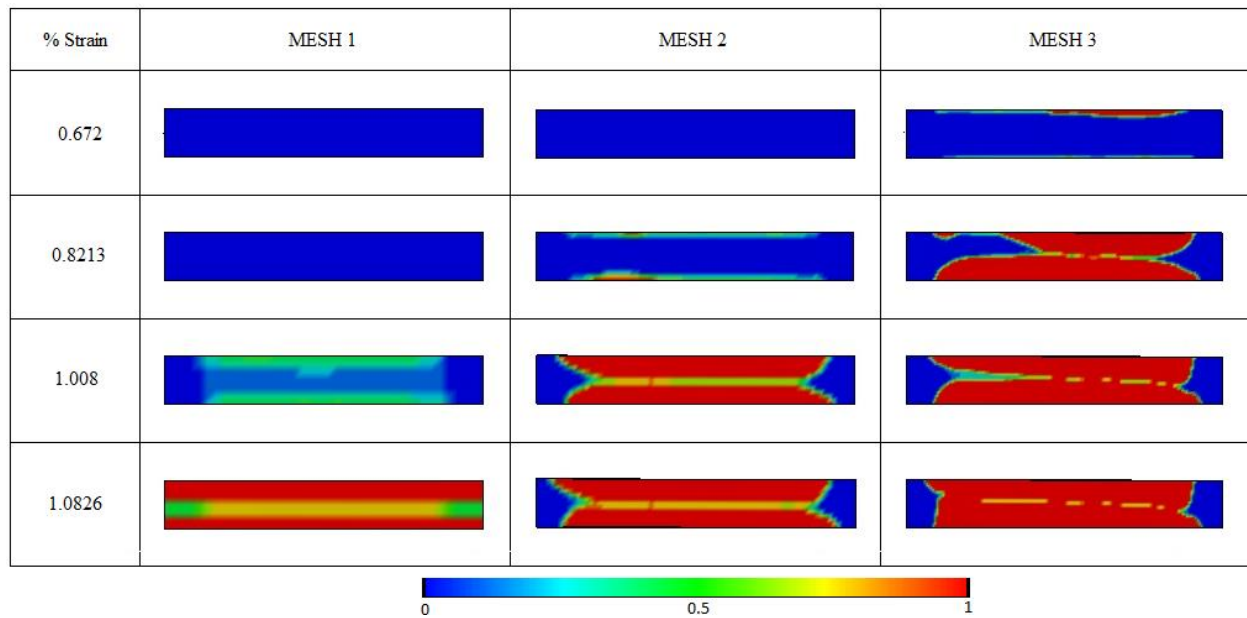
Fig. 2 Perpendicular Matrix damage – Local, in the +45 ply at different displacements

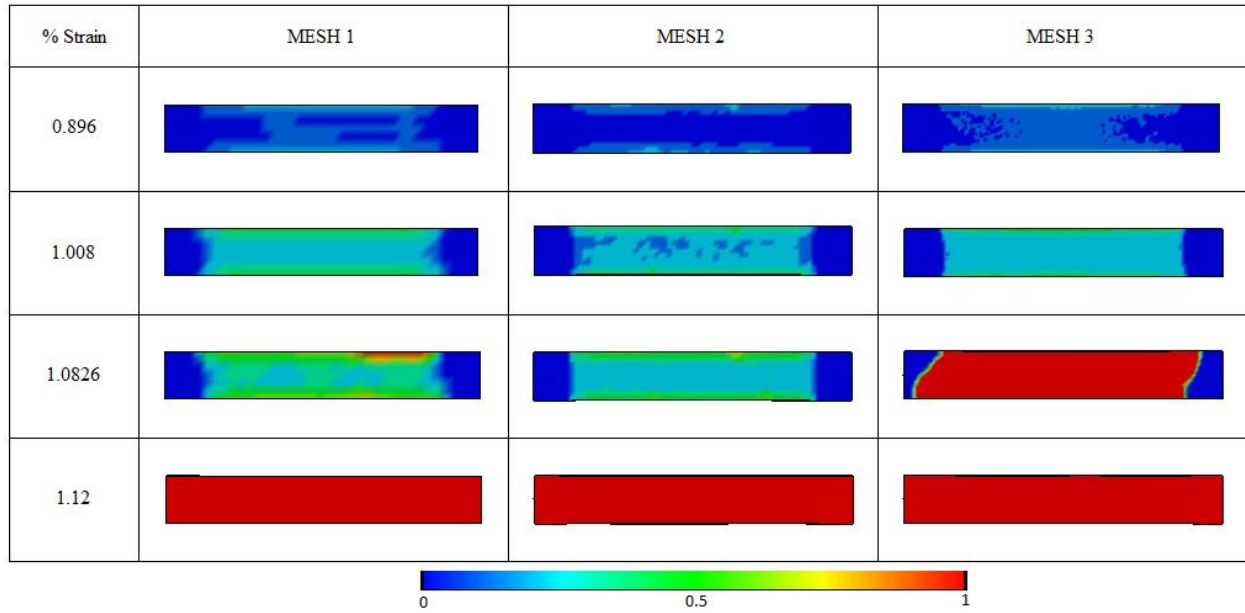| % Strain	MESH 1	MESH 2	MESH 3
0.896			
1.008			
1.0826			
1.12			

0   0.5   1

Fig. 3 Perpendicular Matrix damage – Nonlocal, in the +45 ply at different displacements

Damage in the material, primarily occurs in the +45 ply. The MAT162 damage criteria differentiates matrix damage into matrix damage on planes perpendicular and parallel to the fiber direction [18]. The presence of parallel matrix damage indicates the delamination failure mode. The damage growth profiles for the perpendicular matrix (intralaminar) damage mode in the +45 ply using the local and nonlocal model are shown in Fig. 2 and 3 respectively as a function of the axial strain in the material obtained by dividing the total displacement by the initial length of the laminate. The mesh dependency of the local framework can be observed, as the meshes become finer the strains get localized and damage occurs at smaller strain value with increasing mesh density. Whereas, the nonlocal meshes have similar results. The damage initiation occurs at approximately the same displacement and the profiles are consistent across the meshes.
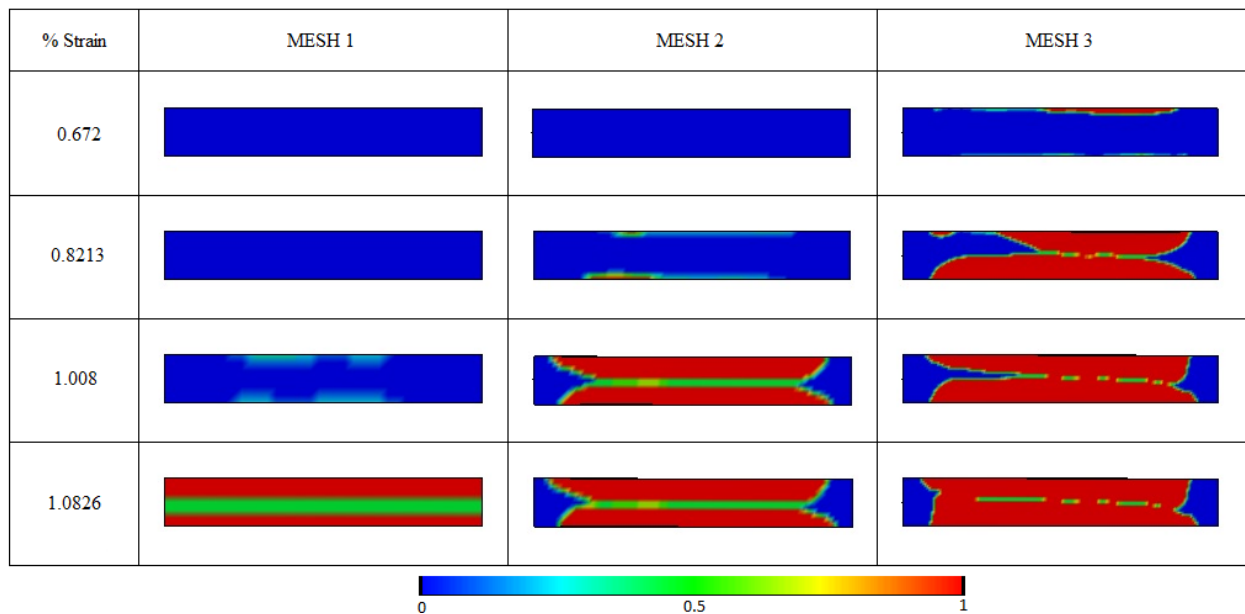
% Strain	MESH 1	MESH 2	MESH 3
0.672			
0.8213			
1.008			
1.0826			

0   0.5   1

Fig. 4 Parallel Matrix damage – Local, in the +45 ply at different displacements

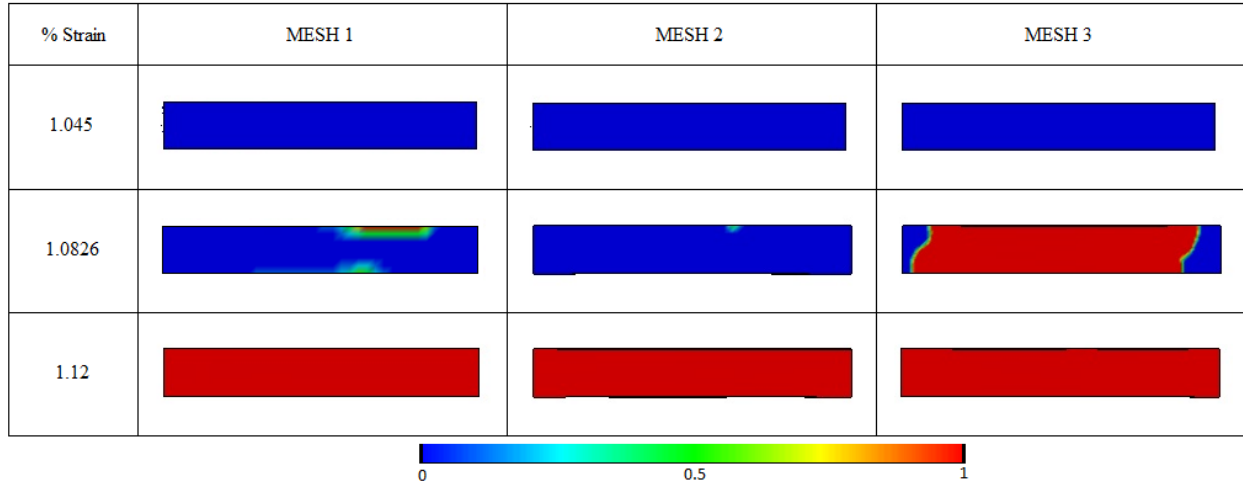| % Strain	MESH 1	MESH 2	MESH 3
1.045			
1.0826			
1.12			

Fig. 5 Parallel Matrix damage – Nonlocal, in the +45 ply at different displacements

The parallel matrix damage profiles shown in Fig. 4 and Fig. 5 display a similar trend. The nonlocal damage occurs at around 1.6 mm displacement and propagates very quickly whereas in the local model parallel matrix damage is predicted much earlier and the profile follows the perpendicular matrix damage profile shown in Fig. 2.

The final failure occurs when the fiber tension/shear mode is predicted. The final damage profiles for the 0 ply are shown in Fig. 6. The local model tends to concentrate strains as the elements get smaller. This occurs closer to the location where boundary condition is applied in the local models and therefore failure is predicted at these locations. Fiber failure tends to occur closer to the center in the nonlocal models as there is reduced effects of stress concentrations from the boundary conditions.
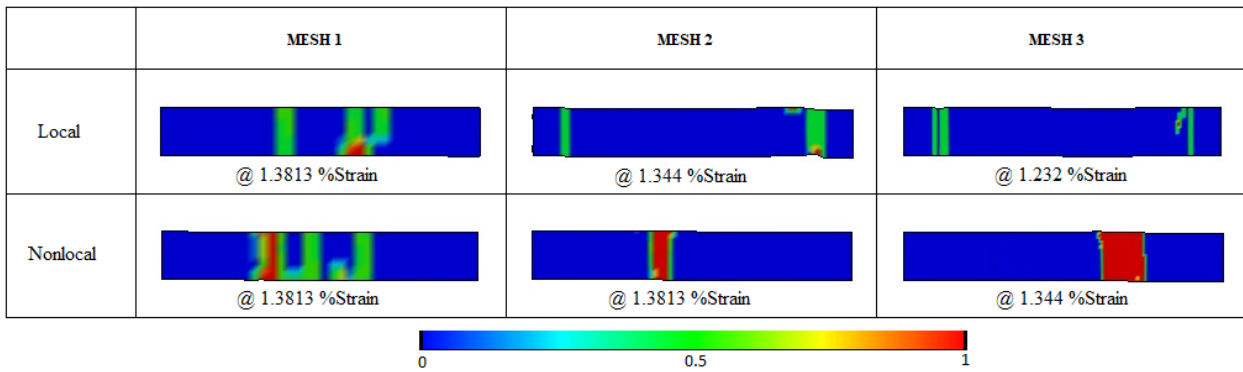
	MESH 1	MESH 2	MESH 3
Local	@ 1.3813 %Strain	@ 1.344 %Strain	@ 1.232 %Strain
Nonlocal	@ 1.3813 %Strain	@ 1.3813 %Strain	@ 1.344 %Strain

Fig. 6 Fiber tension/shear damage – Local and Nonlocal, in the 0 ply at final failure

Fig. 7 Load – Displacement Curve for all meshes

The load displacement curve is shown in Fig. 7 obtained from the nodal forces at the prescribed motion boundary condition. The initial load drop in the curves are when parallel matrix cracks are predicted in the +45 ply. The final failure occurs when fiber damage is predicted in the 0 ply. The damage in the nonlocal models occurs at similar applied displacements and the curves show similar results across the three meshes.
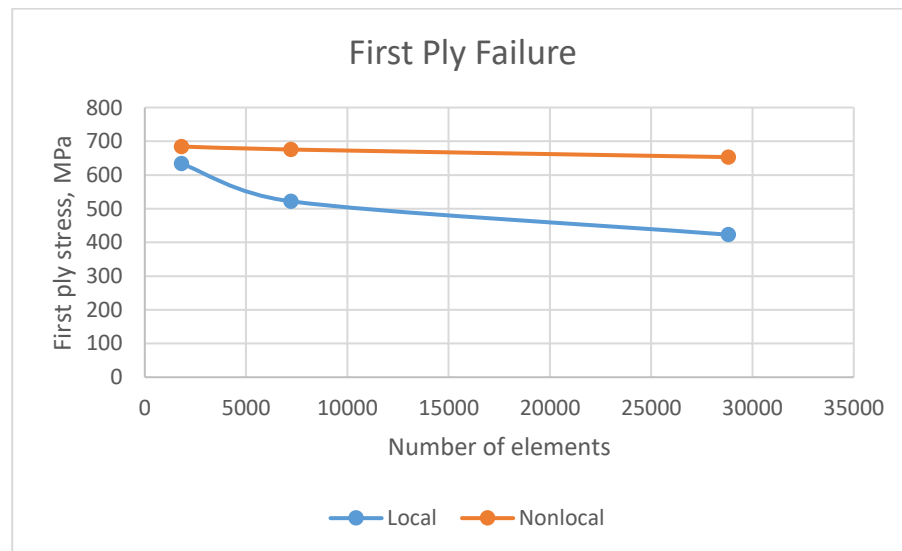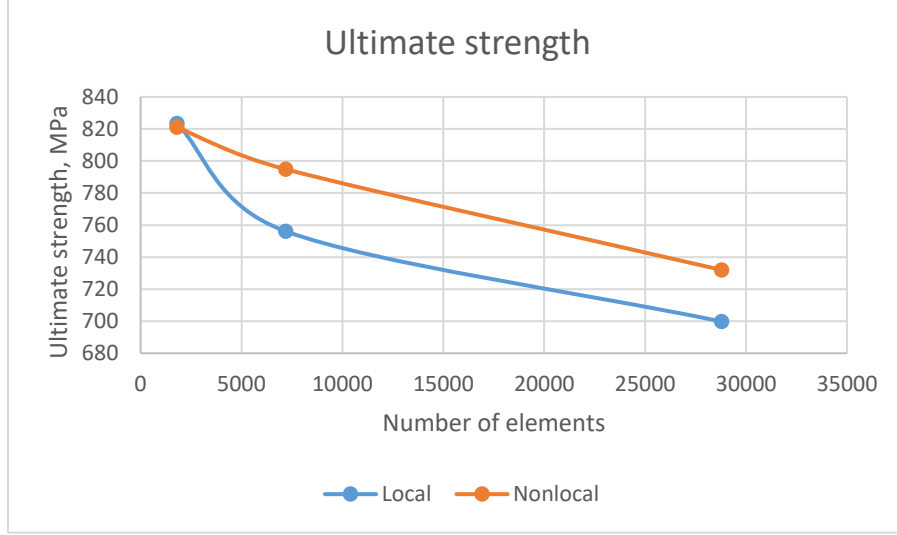

Fig. 8 Predicted First ply failure

Fig. 9 Predicted Ultimate Strength

The first ply failure (FPF) strength and the ultimate failure strength of the laminate are plotted in Fig. 8 and Fig. 9. The FPF strengths are consistent across the different meshes for the nonlocal models. The nonlocal models show a drop in the value of the ultimate strength with increasing element density. The deviation in the nonlocal models is however smaller than the local counterpart. This could be attributed to the isotropic 2D averaging formulation of the nonlocal model. Future studies will look into the 3D anisotropic averaging formulation.

IV. Conclusions

In this work, the MAT162 progressive damage model has been coupled with a nonlocal model and developed as a fortran user material subroutine in the LS-DYNA environment. The advantages of the nonlocal formulation are highlighted by comparing the results with and without the nonlocal formulation at different mesh densities for an 8-ply laminate under tension. The numerical analysis exhibits the regularization achievable using a nonlocal approach. It can be concluded that using the nonlocal approach, an analysis can be conducted with reasonably coarser meshes and predict physically sound mesh independent – regularized results.

Acknowledgments

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