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Deformation and failure analyses of cross-ply laminates using a nonlocal discrete model

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ABSTRACT

A novel nonlocal discrete model is proposed in this paper to study the deformation and failure behaviors of cross-ply laminated composite plate under static or quasi-static mechanical loadings. Different from existing numerical approaches, the proposed model accounts for the material anisotropy at both constitutive and structural level. To achieve this purpose, the proposed model rotates the underlying topological structure, rather than transforming the material's tangent stiffness matrix as in the continuum-based simulations. Thus, different failure behaviors can be modeled as the natural outcome of the breakage of connecting springs. The proposed model is verified and validated by comparing the simulation results with analytical solution and experimental observations from open literature.

1. Introduction

Due to its high strength and stiffness to weight ratios, among many other superior properties, laminated composite structure has been extensively used in various engineering applications, such as aerospace, automotive and shipbuilding industries. Extensive research works have been done on understanding the various mechanical behaviors of the structure both numerically and experimentally. Detailed reviews on computational models for laminated composite plates and shells can be found in [1–4].

Full 3D elasticity analyses [5–10] reveal that the inter-laminar continuity of transverse normal and shear stresses as well as the layer-wise continuous displacement field through the thickness of the laminated structure are essential requirements for analyses of this type of structure. The inherent anisotropy and mismatch of material properties, e.g., modulus and Poisson's ratios, between plies result in high inter-laminar stresses [11–15], which is critical to the delamination failure [16]. Most existing computational approaches are continuum-based and are more suitable before the discontinuities occur, such as cracking and delamination. For failure problems involving moving discontinuities, Continuum Mechanics-based approaches become very difficult to be applied even though there are many numerical techniques available in the literature to handle discontinuities, such as the cohesive elements [17], and the eXtended Finite Element Method (XFEM) [18].

Comparing to Continuum Mechanics-based computational tools, the discrete formulation-based approaches have intrinsic advantages in failure analyses of composite structures, such as Discrete Element Method (DEM) [19–21] and Peridynamics [22–24]. These models do not require external criteria and rules to guide any fracture behaviors, such as initiation, propagation, branching and coalescence. Different fracture behaviors can be naturally captured via breakage of connecting bonds. Recently, Chen et al. [25,26] has developed a nonlocal lattice particle model for studying the deformation and fracture behaviors of 2D homogeneous isotropic materials. Different from other discrete models, the developed lattice particle model introduces a nonlocal interaction between interacting discrete particles. With this nonlocal interaction, the constraint on Poisson's ratio which is fixed to 0.25 for classical lattice models has been completely removed [25] and the issue of pathological dependence for fracture simulation using regular lattice structures has been solved [26]. This approach was extended for 2D anisotropic materials [27], 2D polycrystalline materials [28], and 3D homogeneous isotropic materials [29]. Unlike the traditional way of representing the material orientation by transformation of material tangent stiffness matrix, the lattice particle model treats the material orientation by rotating the topological lattice structure accordingly. By doing this, not only the material orientation is accurately represented, but also eliminates the mesh dependency in some other computational models [30].

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In this study, the lattice particle methodology is extended to model the deformation and especially failure behaviors of 3D cross-ply laminated composite structures. The remainder of this paper is organized as follows: in Section 2, the formulation and derivation of the lattice particle model for orthotropic material is discussed. The lattice rotation scheme for accurate material orientation representation, the geometric modeling of laminated composite structure and interface modeling are also discussed. A spring based failure criterion is proposed for fracture modeling. Section 3 presents numerical verification and validation study. Discussions and conclusions based on current study are drawn in Section 4.

2. Proposed simulation methodology

2.1. Extension of nonlocal discrete model to orthotropic material

In the proposed lattice particle model, the domain of interest is decomposed into regularly packed discrete units, or particles. Each particle interacts with its neighbors via springs. In this study, the simple cubic packing with both the first and the second nearest neighboring particles as interacting neighbors is considered. A unit cell is defined as the repeating non-overlapping unit identified from the domain decomposition. A schematic for the simple cubic packing and the two unit cells is shown in Fig. 1.

As can be seen in Fig. 1, there are six nearest neighbors associated with unit cell 1 and twelve second nearest neighbors with unit cell 2. The volumes of these two unit cells in terms of the particle radius R can be calculated as $V_1 = (2R)^3 = 8R^3$ and $V_2 = \frac{16\sqrt{3}}{9}\left(\frac{\sqrt{6}}{2}\left(\sqrt{2}R\right)\right)^3 = 16R^3$. The 18 normal unit vectors are given in Table 1.

The key component in the lattice particle formulation is the potential energy for each particle. This potential energy eventually determines the interactions between the particles, i.e., local or non-local. Different from most other discrete models, the proposed model introduces a nonlocal potential which has the following form

$$U_{particle} = \sum_{I=1}^{2} U_{cell\_I} = \sum_{I=1}^{2} (U_{local\_I} + U_{nonlocal\_I}) \tag{1}$$

where U_{local_I} and $U_{nonlocal\_I}$ are the local and nonlocal energies as

$$U_{local\_I} = \frac{1}{2}\sum_{J=1}^{N_I} k_{IJ}(\delta l_{IJ})^2 \tag{2}$$

$$U_{nonlocal\_I} = \frac{1}{2}\left(\sum_{J=1}^{N_I} T_{IJ}\delta l_{IJ}\right)\left(\sum_{J=1}^{N_I}\delta l_{IJ}\right) \tag{3}$$

where k_{IJ} and T_{IJ} are the local and nonlocal spring parameters, δl_{IJ} is the half elongation, I and J is the index of the particles, N_I is the number of neighbors for unit cell I.

Table 1
The unit normal vectors for simple cubic structure.

Neighbors 1 ($N_1 = 6$)		Neighbors 2 ($N_2 = 12$)			
1	$(1,0,0)$	7	$1/\sqrt{2}(1,1,0)$	13	$1/\sqrt{2}(1,0,-1)$
2	$(-1,0,0)$	8	$-1/\sqrt{2}(1,1,0)$	14	$1/\sqrt{2}(-1,0,1)$
3	$(0,1,0)$	9	$1/\sqrt{2}(1,-1,0)$	15	$1/\sqrt{2}(0,1,1)$
4	$(0,-1,0)$	10	$1/\sqrt{2}(-1,1,0)$	16	$-1/\sqrt{2}(0,1,1)$
5	$(0,0,1)$	11	$1/\sqrt{2}(1,0,1)$	17	$1/\sqrt{2}(0,1,-1)$
6	$(0,0,-1)$	12	$-1/\sqrt{2}(1,0,1)$	18	$1/\sqrt{2}(0,-1,1)$

Given the local and nonlocal energies, the potential energy for each unit cell can be rewritten in terms of the components of the strain tensor as

$$U_{cell\_I} = \frac{\left(l_0^I\right)^2}{2}\sum_{b=1}^{N_I} k_{Ib} n_i^b \varepsilon_{ij} n_j^b n_k^b \varepsilon_{kl} n_l^b + \frac{\left(l_0^I\right)^2}{2}\left(\sum_{b=1}^{N_I} T_{Ib} n_i^b \varepsilon_{ij} n_j^b\right)\left(\sum_{b=1}^{N_I} n_k^b \varepsilon_{kl} n_l^b\right) \tag{4}$$

with $i, j, k, l = 1, 2, 3$, l_0^I is half of the original length between the reference particle and its Ith nearest neighbors. n_i^b is the ith component of the spring b given in Table 1.

Due to the conservative of the potential, the material tangent stiffness matrix can be obtained by differentiating the total specific energy with respect to the strain tensor twice as

$$C_{ijkl} = \frac{1}{V_1}\frac{\partial^2 U_{cell\_1}}{\partial\varepsilon_{ij}\partial\varepsilon_{kl}} + \frac{V_2}{V_1}\left(\frac{1}{V_2}\frac{\partial^2 U_{cell\_2}}{\partial\varepsilon_{ij}\partial\varepsilon_{kl}}\right) \tag{5}$$

It should be noted that the Voigt notation for the material stiffness matrix has been adopted in Eq. (5).

Using the unit normal vectors given in Table 1, the following correspondence can be obtained by comparing the coefficients of the material tangent stiffness matrices as

$$\begin{aligned}
C_{11} &= \frac{1}{4R}(k_1 + k_7 + k_{11} + 2T_1 + 8T_7 + 8T_{11});\\
C_{22} &= \frac{1}{4R}(k_3 + k_7 + k_{15} + 2T_3 + 8T_7 + 8T_{15})\\
C_{33} &= \frac{1}{4R}(k_5 + k_{11} + k_{15} + 2T_5 + 8T_{11} + 8T_{15});\\
C_{13} &= \frac{1}{4R}(k_{11} + T_1 + T_5 + 4T_7 + 8T_{11} + 4T_{15})\\
C_{12} &= \frac{1}{4R}(k_7 + T_1 + T_3 + 8T_7 + 4T_{11} + 4T_{15});\\
C_{23} &= \frac{1}{4R}(k_{15} + T_3 + T_5 + 4T_7 + 4T_{11} + 8T_{15})\\
C_{44} &= \frac{1}{4R}k_{15};\ C_{55} = \frac{1}{4R}k_{11};\ C_{66} = \frac{1}{4R}k_7
\end{aligned} \tag{6}$$

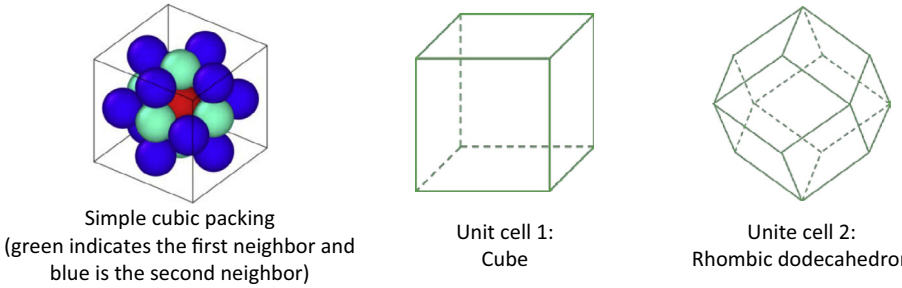

Fig. 1. The simple cubic lattice structure and the unit cells.